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ARTICULATED BUS DYNAMIC ANALYSIS

THE UNIVERSITY OF MICHIGAN
HIGHWAY SAFETY RESEARCH INSTITUTE

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ARTICULATED BUS DYNAMIC ANALYSIS

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Technical Memorandum

Prepared for:

The Ontario Ministry of Transportation and Communications

by

Highway Safety Research Institute
The University of Michigan

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Ontario

Ministry of
Transportation and
Communications

Research and Development Branch,
1201 Wilson Avenue,
Downsview, Ontario.
M3M 1J8

May 14, 1981

Mr. P.S. Fancher, Jr.,
Highway Safety Research Institute,
Huron Parkway and Baxter Road,
Ann Arbor, Michigan 48109

Ref: MTC Project 31401

Dear Paul:

With apologies for the delay in writing, this letter is to thank you for the final report entitled "Articulated Bus Dynamic Analysis". I have examined it in some detail, and am very pleased with the contents. It provides the test recommendations we requested with ample background details, and as you know it will be implemented as part of the GM bus testing program. The report has been accepted by MTC, fulfilling the contract requirements.

We have discussed release of the report with GM and I can now approve your filing a copy in the HSRI library, provided the Appendices A,B,C,D are removed. I trust that this is satisfactory to you.

I hope to be contacting you shortly concerning possible further simulation work, on failure modes of the articulated bus systems.

Yours very truly,

A.M. Billing,
Project Research Officer.

c.c. M.D. Harmelink
F.B. Snelgrove

PROJECT SUMMARY

TITLE: Articulated Bus Dynamic Analysis

SPONSOR: Ontario Ministry of Transportation and Communications

PERIOD: November 1980 - January 1981

Computer simulation was used in this study to provide the basis for a pretest evaluation of the dynamic response characteristics of a specific articulated bus design of particular interest to the Ontario Ministry of Transportation and Communications. Hypothesized control challenges (e.g., instability caused by wheel lock when braking in a turn, etc.) were developed, examined through computer simulation, and to the extent possible, compared with the performance of a standard transit bus, a tractor-semitrailer vehicle, or an articulated bus without any special device for controlling articulation angle. The results were reviewed to suggest vehicle tests which would verify the accuracy of the analytical predictions of (1) basic capabilities and (2) any control problems.

ACKNOWLEDGEMENT

Liaison with the Highway Safety Research Institute was provided by Mr. Alan Billing of the Ministry of Transportation and Communications. His help in describing the vehicle and discussing its response properties is gratefully acknowledged.

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1.0 INTRODUCTION

This report presents (1) a pretest evaluation of the dynamic response characteristics of a specific articulated bus of particular interest to the Ontario Ministry of Transportation and Communications (MTC) and (2) test procedures for examining the response of this bus to control inputs. These results are based on analytical work performed by the Highway Safety Research Institute (HSRI) of The University of Michigan.

The following methodology was employed in analyzing the response of the articulated bus to control inputs at the steering wheel, brake, and accelerator. First, all available data describing the bus and its components were studied to deduce parametric values suitable for use in computer calculations. A computerized model [1] developed by HSRI for simulating the braking and steering dynamics of tractor-semitrailer vehicles was revised and extended to include appropriate control features at the articulation joint, thereby providing a computerized model of the bus. Through a process consisting of (1) developing the vehicle model, (2) estimating parametric values for describing the bus, (3) performing linear analyses and simplified braking calculations, (4) discussing conditions that may be challenging to bus drivers, and (5) making engineering judgments concerning practical vehicle tests, the following matters were chosen for examination using computer simulation:

a) directional response in sudden turning and obstacle-avoidance (lane-change) maneuvers,

b) response to a perturbation during high speed, straight-line driving,

c) cornering with drive thrust on a low friction surface with and without wheel spin, and

d) control difficulties arising during braking-in-a-turn maneuvers.

The next section of this report (Section 2.0) presents an evaluation of the response of the subject vehicle based on analytical predictions. Section 3.0 discusses test procedures that would (1) verify the accuracy of the analytical predictions and (2) serve to delineate control problems. Concluding statements summarizing the findings of this study are presented in Section 4.0.

The main body of the report is supported by appendices containing (a) the parametric values used to describe the vehicle, (b) time histories from the matrix of runs performed in analyzing the vehicle, (c) results from linear analyses of directional response, and (d) simplified calculations used for estimating braking performance.

2.0 PREDICTIONS OF THE RESPONSE CHARACTERISTICS OF THE ARTICULATED BUS

This section presents results of the computer simulation study that was used to predict the response of the articulated bus in six different vehicle maneuvers. The basic configuration of the articulated bus examined here is similar to that of a three-axle tractor-semitrailer, but differing in having: (a) a non-powered two-axle lead unit, (b) a powered single-axle rear unit connected to the lead unit by an articulation joint located well aft of the center axle, and (c) an active torque control device at the articulation pivot. The two important properties of rear-axle drive and active articulation angle control make this a particularly unique vehicle. In this regard, comparison of vehicle responses with other more conventional vehicles may not seem entirely justified or appropriate, but nevertheless, is done in some instances in this section. Its main purpose is only to verify no unusual departures in basic response numerics of the articulated bus from those of somewhat similar vehicles.

All simulation results and numerics summarized in this section (see Appendix B for the complete set of time histories) include the influences of the articulation controller and used the original axle load estimates provided by the MTC. Exceptions to this basic vehicle condition (e.g., subsequent axle load measurements referred to as "New Load Data" and cases excluding the articulation controller) are noted in the following summary of results and in the tables of simulation runs listed in Appendix B.

Baseline data sets for the PHASE 4 computer model are listed in Appendix A for both the empty and loaded vehicle. Also listed in Appendix A are data sets for the "New Load Data" condition, the Standard Bus (single unit), and the baseline data set containing the analytical tire model (in place of tire data tables) used for the low friction and traction/braking simulation runs.

2.1 Directional Response in Turning Maneuvers

2.1.1 Steady Turning Performance. One of the most important directional properties of a vehicle is its behavior in a steady turn. The path curvature achieved in a steady turn is primarily determined by (1) the level of steering input, (2) the wheelbase of the vehicle, (3) velocity of travel, and (4) the mechanical properties of the tires relative to the load they carry.

The simulated, steady-turning response of the articulated bus is shown in Figure 2.1. In this figure the lateral acceleration level in a steady turn is plotted as a function of the steering-wheel angle for the fully loaded and empty conditions, at forward speeds of 50 and 100 KPH. Figure 2.1 indicates that the lateral acceleration gain is very sensitive to both the speed of travel and the loading condition. The empty bus exhibits a much greater sensitivity to steering input than the loaded bus.

A broader understanding of the steady-turning qualities of a vehicle and their implications to stability can be gained by inspecting the basic relationship which exists between the steady-turning response of the vehicle and its design parameters and operating conditions. The path curvature of the articulated bus can be expressed by the following classical relationship:

$$\frac{1}{R} = \frac{\delta_{sw}/N_G}{57.3\,\ell_{1e} + \dfrac{K_1 U^2}{g}} \qquad (1)$$

where

R = radius of curvature of the turn (ft)

δ_{sw} = steering-wheel angle (deg)

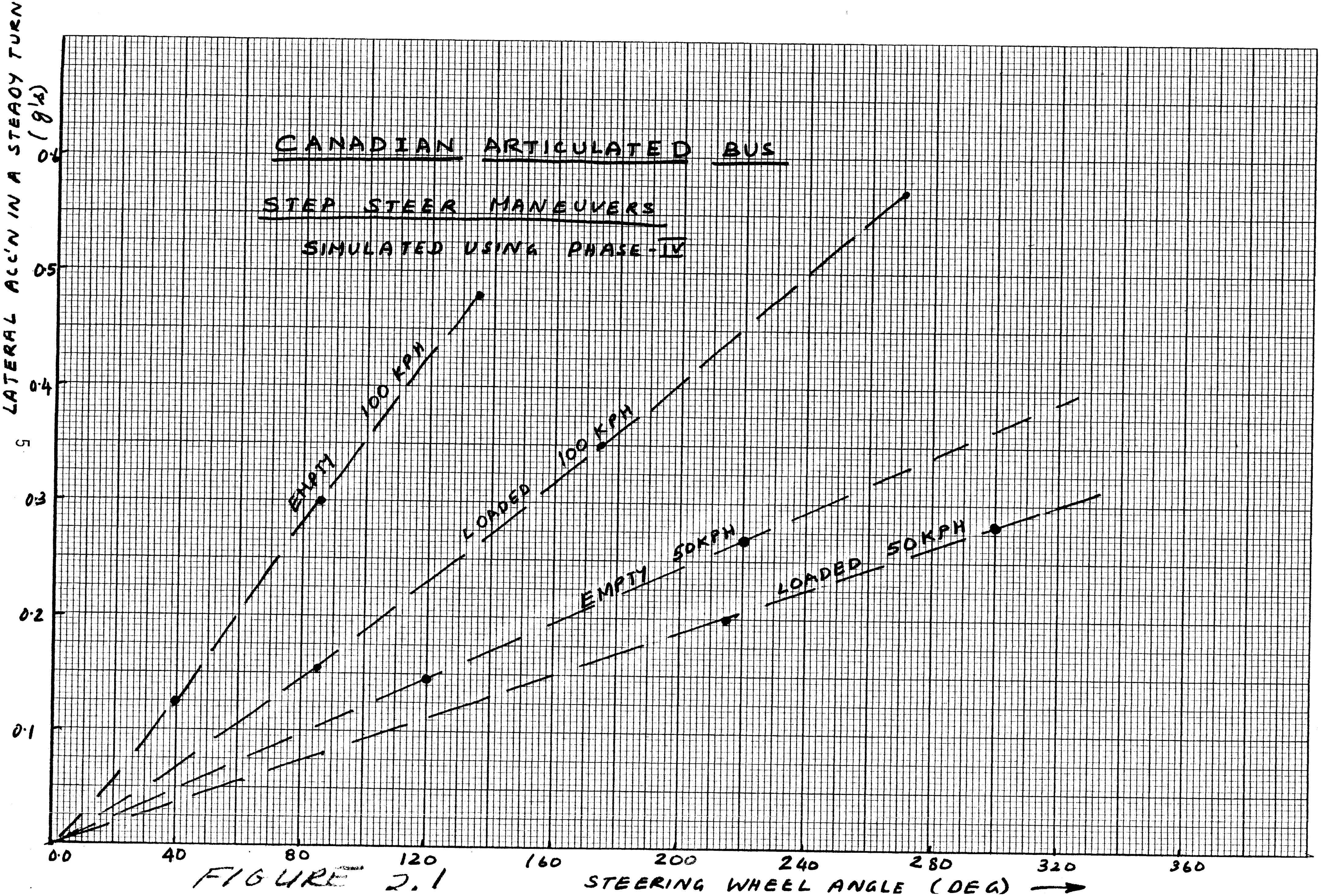
N_G = steering gear ratio

ℓ_{1e} = effective wheelbase of the lead unit (ft)

K_1 = under/oversteer gradient of the lead unit (deg/g)

U = forward velocity of the vehicle (ft/sec)

g = acceleration due to gravity (32.2 ft/sec^2)



CANADIAN ARTICULATED BUS

STEP STEER MANEUVERS

SIMULATED USING PHASE-IV

FIGURE 2.1

With reference to Equation (1), the vehicle is said to be "understeer" when K_1 is positive, "neutral steer" when K_1 is zero, and "oversteer" when K_1 is negative. An understeer vehicle exhibits a stable and finite steady turning response for all forward velocities. In the case of an oversteer vehicle, the denominator of the expression on the right-hand side of Equation (1) decreases with increasing velocity until a value termed the "critical velocity" is reached. At the critical velocity, the denominator goes to zero and the path curvature tends to infinity. The oversteer vehicle is therefore said to be "divergently unstable" for velocities greater than the critical velocity.

Steady turning results (either from simulations of steady turns or from steady-turning experiments) can be used in conjunction with Equation (1) to determine the two parameters, K_1 and ℓ_{1e}. Results from steady-turning simulations of the articulated bus are shown in Figure 2.2 for the empty and loaded conditions. The axes chosen to represent the steady-state results in Figure 2.2 are such that the slope of the line which joins the steady-turning equilibrium parts is the "under/oversteer gradient," K_1, and the intercept on the ordinate is the effective wheelbase, ℓ_{1e}, of the lead unit.

We note that the articulated bus has an understeer level of 4.0 deg/g when empty. When fully loaded the understeer level of the bus is further increased to 10.3 deg/g. The steady-turning response of a standard 35-foot "single unit" bus in the empty condition is also shown in Figure 2.2. It can be seen that the understeer level of the empty articulated bus is almost twice as much as the standard 35-foot bus when empty.

The effective wheelbase predicted by the simulation can also be seen to be very close to the longitudinal distance of 235 inches which exists between the front and rear axles of the lead unit.

Although no low speed, minimum turning diameter simulation runs were performed in this study, results of the low speed (10 ft/sec), low friction turning-with-drive-thrust runs (see Section 2.4) indicated that both the loaded and empty vehicle would turn within a 70-foot diameter

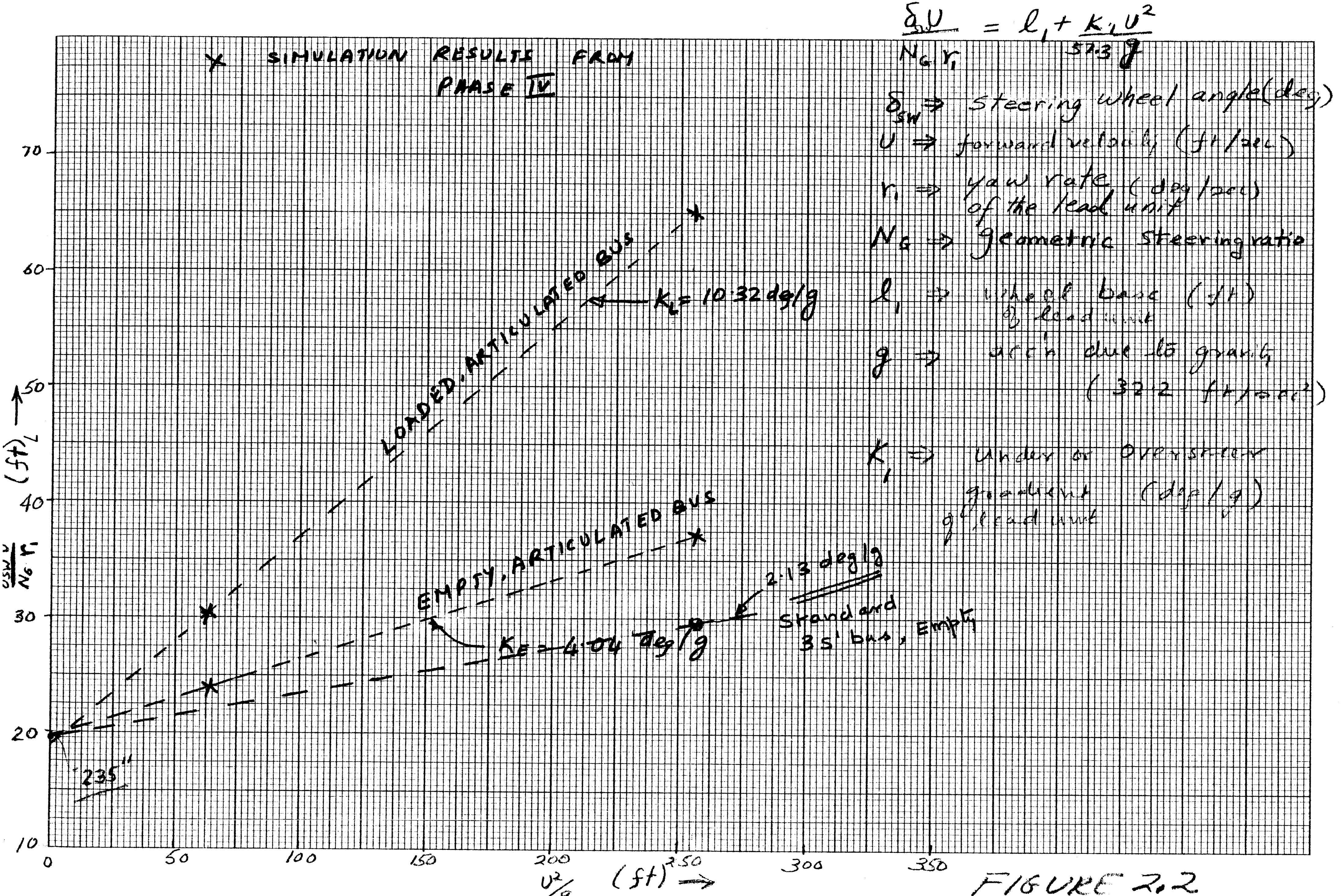

* SIMULATION RESULTS FROM PHASE IV
$\frac{\delta_{SW} U}{N_G r_1} = l_1 + \frac{K_1 U^2}{57.3\, g}$
δ_{SW} ⇒ Steering wheel angle (deg)
U ⇒ forward velocity (ft/sec)
r_1 ⇒ yaw rate (deg/sec) of the lead unit
N_G ⇒ geometric steering ratio
l_1 ⇒ wheel base (ft) of lead unit
g ⇒ acc'n due to gravity (32.2 ft/sec²)
K_1 ⇒ Under or Oversteer gradient (deg/g) of lead unit
LOADED, ARTICULATED BUS
K_L = 10.32 deg/g
EMPTY, ARTICULATED BUS
K_E = 4.04 deg/g
2.13 deg/g
Standard 35' bus, Empty
235"
70
60
50
40
30
20
10
$\frac{\delta_{SW} U}{N_G r_1}$ (ft) →
0
50
100
150
200
250
300
350
U^2/g (ft) →

FIGURE 2.2

for 38 degrees of front wheel angle. The lateral acceleration level achieved in each of these runs was about 0.10 g's. Interpolating the above result to 33 degrees of front wheel angle suggests a minimum turning diameter of approximately 80 feet if the front wheel angle is limited to a maximum of 33 degrees. Higher friction surfaces and lower speeds (understeer contribution gradient) should both work to further reduce the minimum turning diameter indicated above.

The steady-turning response of the trailing unit of the articulated bus is similar to that of a single-unit vehicle which has the rear axle of the lead unit as its steerable axle. Hence, the steady-turning response of the trailer can be expressed by an equation which is similar to (1), viz.:

$$\frac{1}{R} = \frac{\Gamma}{57.3\ \ell_{2e} + \frac{K_2 U^2}{g}} \tag{2}$$

or

$$\Gamma = \frac{\ell_{2e}}{R} \times 57.3 + \frac{K_2 U^2}{gR} \tag{3}$$

where

Γ is the articulation angle (deg)

ℓ_{2e} is the effective wheelbase of the trailing unit (ft)

K_2 under/oversteer gradient of the trailing unit (deg/g)

Analysis performed in Reference [ ] indicates that K_2 does not have the same stability connotation as the under/oversteer gradient, K_1, of the lead unit. While K_1 is the vehicle characteristic which establishes whether the articulated vehicle is statically stable or not, K_2 determines the nature of the instability, i.e., whether the instability would result in a tractor jackknife or a trailer swing.

The steady-turning behavior of the trailing unit in the fully loaded and empty conditions is presented in Figure 2.3. The trailing

$$\frac{\Gamma U}{r} = l + \frac{K U^2}{57.3g}$$

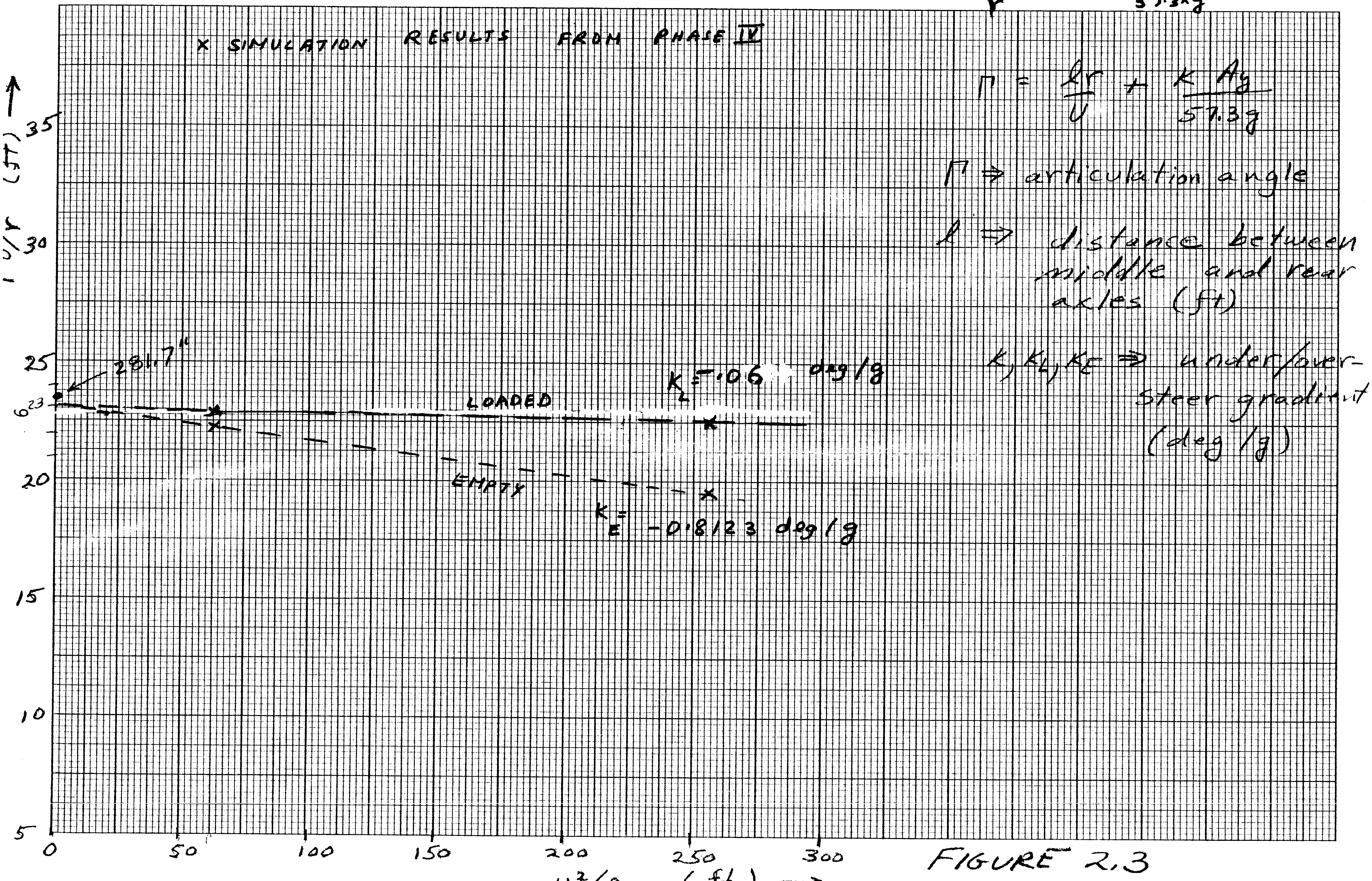


FIGURE 2.3

unit is found to exhibit an oversteer level of -.06 deg/g when empty. The oversteer level of the trailer increases to -0.8 deg/g when fully loaded. These results indicate that, for a turn of fixed radius, R, the articulation angle would decrease a small amount as the forward velocity is increased. The effective wheelbase of the trailing unit is only slightly smaller than the longitudinal distance of 281.7 inches which exists between the tractor rear axle and the trailer's axle. The fact that the trailer is predicted to be oversteer is probably not significant. The finding that $|K_2|$ is small corresponds to the situation for a typical tractor-semitrailer vehicle and is the basis for predicting that the articulation angle will be determined primarily by the wheelbase between the middle and rear axles of the bus and the radius of the turn at all forward speeds—in other words, the tracking of the trailing unit of the bus should be very good in a steady turn.

2.1.2 Response Time in Ramp-Step Maneuvers. Computer simulation numerics for the ramp-steer test described in Section 3.1 are presented in Tables 2.1-2.4. Corresponding time histories are shown in Appendix B as Runs #1.1-1.12. Each table corresponds to a different loading or velocity condition. The first two columns in each table list the steering-wheel angle input and the resulting steady-state lateral acceleration. The yaw rate and lateral acceleration response times, shown in columns 3 and 4, are defined as the length of time from when the steering-wheel input reaches 50 percent of its steady input level to when the response (yaw rate/lateral acceleration) reaches 90 percent of its steady-state value. The Yaw Rate % Overshoot numeric is simply the percent by which the yaw rate overshoot exceeded its steady-state value. Yaw Rate Oscillation Period is an approximate measure of the period of oscillation (if any) displayed by the yaw rate response.

In addition to the response numerics shown for the articulated bus, Table 2.1 includes similar numeric calculations for an empty standard (single-unit) bus at 100 KPH. Comparison of the standard bus and articulated bus step-steer numerics, indicates about 20 percent slower response times in both yaw and lateral motions for the standard bus. This result should suggest that drivers of standard buses would

Table 2.1. Ramp-Step Steer Numerics
(Empty, 100 KPH)
Runs #1.1-1.3, 1.12

	Steering-Wheel Input	S.S. Lateral Accel. (g)	Yaw Rate Response Time (sec)	Lateral Accel. Response Time (sec)	Yaw Rate % Overshoot	Yaw Rate Oscillation Period (sec)
Lead Unit	40	0.12	0.87	1.45	7	--
	85	0.30	1.02	1.77	2	--
	135	0.48	1.20	2.12	0	--
Trail Unit	40	0.12	1.10	1.57	27	2.6
	85	0.30	1.17	1.77	18	2.8
	135	0.48	1.22	2.0	20	3.1
Standard Bus	40	0.16	1.12	1.87	0	--

Table 2.2 Ramp-Step Steer Numerics
(Loaded, 100 KPH)
Runs #1.6-1.8, 1.11

	Steering-Wheel Input	S.S. Lateral Accel. (g)	Yaw Rate Response Time (sec)	Lateral Accel. Response Time (sec)	Yaw Rate % Overshoot	Yaw Rate Oscillation Period (sec)
Lead Unit	85	0.16	0.57	1.30	17	3.6
	175	0.36	0.67	1.70	12	--
	270	0.57	1.18	2.28	0	--
	85 (No Controller)	0.17	0.57	1.3	17	3.6
Trail Unit	85	0.16	0.90	1.45	50	2.8
	175	0.36	1.02	1.75	36	3.2
	270	0.57	1.25	2.35	12	3.5
	85 (No Controller)	0.17	0.90	1.45	50	2.8

Table 2.3. Ramp-Step Steer Numerics
(Empty, 50 KPH)
Runs #1.4-1.5

	Steering-Wheel Input	S.S. Lateral Accel. (g)	Yaw Rate Response Time (sec)	Lateral Accel. Response Time (sec)	Yaw Rate % Overshoot	Yaw Rate Oscillation Period (sec)
Lead Unit	120	0.15	0.82	1.15	0	--
	220	0.26	0.90	1.22	1	--
Trail Unit	120	0.15	1.32	1.57	6	2.6
	220	0.26	1.39	1.70	7	2.8

Table 2.4. Ramp-Step Steer Numerics
(Loaded, 50 KPH)
Runs #1.9-1.10

	Steering-Wheel Input	S.S. Lateral Accel. (g)	Yaw Rate Response Time (sec)	Lateral Accel. Response Time (sec)	Yaw Rate % Overshoot	Yaw Rate Oscillation Period (sec)
Lead Unit	215	0.20	0.7	0.9	0	--
	300	0.28	0.95	1.45	0	--
Trail Unit	215	0.20	1.2	1.55	7	3.0
	300	0.28	1.4	1.8	5	2.8

not find it necessary to make unusual adjustments to their basic control strategy when operating the articulated bus examined here. The articulated bus should seem to respond slightly quicker to steer inputs, but require somewhat greater steering-wheel input for the same turn (lower gain).

In another comparison, an on-going study by HSRI for the Federal Highway Administration [3], which involves testing of various tractor-trailer combination vehicles, indicates that a particular three-axle tractor-trailer vehicle (with 12,000/20,000/20,000 lb axle loadings) exhibits little or no trailer oscillations during ramp-step maneuvers, but possesses very similar yaw rate response times as the articulated bus.

2.2 Response to a Perturbation

Numerics for the computer simulation results of the pulse-steer maneuver (Test #2), described in Section 3.2, are listed in Table 2.5. (See Appendix B, Runs #2.1-2.6 for the corresponding time histories.) The ratios shown in this table are ratios of the first-to-second peaks for each of the respective responses (trail unit yaw rate, lateral acceleration, and articulation angle). The last column lists the time between corresponding peaks of the articulation angle response.

These results reflect the increased yaw and articulation damping (larger ratio values) that accompany decreased vehicle velocity. Removal of the articulation hinge controller is seen to have little effect on the yaw and articulation damping. Presence of the controller primarily acts to increase lateral acceleration damping and decrease the period of oscillation. The "New Load Data" run (see Appendix A), which resulted in a rearward shift of the trail unit c.g. from approximately two feet in front of the rear axle to about one foot, exhibits reduced yaw, articulation, and lateral acceleration damping from its baseline counterpart (Run #2.1).

Table 2.5. Pulse-Steer Numerics
(120° Steer Level)

Test Condition	Trail Unit Yaw Rate Ratio	Articulation Angle Ratio	Trail Unit Lateral Acceleration Ratio	Time Between Γ Peaks (sec)
Empty, 100 KPH, Run #2.1	2.9	2.2	11.8	0.9
Empty, 50 KPH, Run #2.2	5.0	6.2	5.9	1.0
Empty, 100 KPH, No Controller Run #2.5	2.9	2.4	5.3	1.2
Loaded, 100 KPH, Run #2.3	2.0	1.7	3.1	0.9
Loaded, 50 KPH, Run #2.4	5.7	8.4	12.9	1.1
Empty, 100 KPH, New Load Data, Run #2.6	2.1	1.7	4.1	1.0

2.3 Closed-Loop Response in Accident-Avoidance Lane Changes

Vehicle-related numerics derived from the simulated closed-loop test maneuver described in Section 3.3, are presented in Tables 2.6 and 2.7. (Corresponding time histories appear in Appendix B as Runs #3.1-3.10.) The numerics listed in these tables are essentially open-loop measures of the lead vehicle response in yaw and lateral acceleration to steering-wheel inputs. Table 2.6 shows the influence of varying the distance (column 1) in which to perform the 12-foot lane change for both the empty and loaded vehicles at a speed of 100 KPH. Table 2.6 indicates how driver preview ("look-ahead time") influences the manner in which the driver/vehicle system (empty and loaded) responds in performing the 12-foot lane change within a fixed distance of 150 feet. The principal influence of each of these parameter variations is to cause different levels of peak lateral acceleration to be achieved during the maneuver. Even though none of these runs produced peak lateral acceleration levels above 0.2 g's, the basic maneuver scenario presented here would appear to be a fairly representative and common high-speed maneuver performed on freeways for purposes of obstacle avoidance or simple maneuvering. None of the computer runs performed for this test maneuver indicated any control problems for the driver/vehicle system examined here.

The cross-correlation lags appearing in Tables 2.6 and 2.7 represent that amount of time lag between steering-wheel input and the resulting response variables (lead unit yaw rate, lateral acceleration) to produce maximum cross-correlation. The values shown here were obtained by simple manual shifting of the steering-wheel time history, with respect to the response variable time history, to obtain an "eyeball" maximum correlation. The Amplification Ratio, column 4, is simply the ratio of peak trail unit lateral acceleration to peak lead unit lateral acceleration experienced during the simulated maneuver.

The cross-correlation numerics shown in Tables 2.6 and 2.7 demonstrate little sensitivity to either load condition or parameter variations, although some of this apparent insensitivity probably

Table 2.6. High-Speed Lane-Change Numerics (Empty, 100 KPH, Preview Parameter = 1.75 sec)

	Cross-Correlation Lags			
Lane-Change Distance (ft)	Lead Unit Yaw Rate/ Steer (sec)	Lead Unit Lateral Acceleration/ Steer (sec)	Amplification Ratio A_{y_2}/A_{y_1}	Average Peak Acceleration of Lead Unit (g)
125 (Run #3.1)	0.4	0.7	1.26	0.15
150 (Run #3.3)	0.4	0.7	1.25	0.14
175 (Run #3.5)	0.4	0.7	1.21	0.13
		(Loaded, 100 KPH)		
125 (Run #3.6)	0.4	0.7	1.45	0.14
150 (Run #3.8)	0.4	0.7	1.40	0.13
175 (Run #3.10)	0.4	0.7	1.35	0.12

Table 2.7. High-Speed Lane-Change Numerics (Empty, 100 KPH, Lane-Change Distance = 150 ft)

Driver Preview Parameter (sec)	Cross-Correlation Lags		Amplification Ratio A_{y_2}/A_{y_1}	Average Peak Acceleration of Lead Unit (g)
	Lead Unit Yaw Rate/ Steer (sec)	Lead Unit Lateral Acceleration/ Steer (sec)		
1.5 (Run #3.2)	0.4	0.7	1.30	0.18
1.75 (Run #3.3)	0.4	0.7	1.25	0.14
2.0 (Run #3.4)	0.4	0.7	1.16	0.11
		(Loaded, 100 KPH)		
1.5 (Run #3.7)	0.4	0.7	1.49	0.16
1.75 (Run #3.8)	0.4	0.7	1.40	0.13
2.0 (Run #3.9)	0.4	0.7	1.29	0.10

derives from the limited range of maneuver severity achieved in this matrix of runs. The Amplification Ratio numeric does show sensitivity to both vehicle loading and level of peak lateral acceleration. For purposes of comparison with a vehicle somewhat similar in configuration, values of yaw rate cross-correlation lag and amplification ratio measured for the three-axle tractor-trailer (Federal Highway Administration study) referenced above in Section 2.1.2, are approximately 25 percent lower than the corresponding values for the simulated articulated bus (loaded) shown in Tables 2.6 and 2.7.

2.4 Cornering with Drive Thrust on a Low Friction Surface

Simulation results of a descriptive nature, appearing in Table 2.8, attempt to categorize the yaw response of the articulated bus in terms of stable/unstable characteristics, following the application of rear-axle drive torque on a low friction surface ($\mu=0.15$). (See Appendix B, Runs #4.1-4.10 for the corresponding time histories.) The uniqueness of this particular vehicle, with regard to its rear-axle drive, tends to promote "trailer swing" as a frequent form of directional instability, particularly when drive torque sufficient to spin up the rear wheels is applied. This potential problem is, of course, only present on very low friction surfaces such as ice and snow. By contrast, tractor-trailer vehicles with "center-axle drive" would exhibit tractor "jackknife" instabilities under similar circumstances. A question that is posed by the comparison is whether or not drivers of "center-axle drive" vehicles would have an advantage in these cases to more quickly stabilize the vehicle because of immediate motion cues provided to him/her by the unstable lead unit.

The empty and loaded vehicle descriptors of vehicle directional stability shown in Table 2.8 are listed in ascending order of applied drive torque (column 1). The precise definitions of terminology used in the table are listed on the page following Table 2.8. The results presented in the table fall into two basic categories: (1) those in which no rear-axle wheel spin occurs and (2) those that do involve rear-wheel spin. The empty and loaded vehicles remain essentially stable following application of rear-axle drive torque in which no

Table 2.8. Cornering with Acceleration/Low Friction Numerics
(Empty, 10 KPH, 0.15 Mu)

Drive Torque (in-lb)	Articulation Angle Response	Lead Unit Yaw Rate Response	Trail Unit Yaw Rate Response	Rear Axle Wheel Spin
20,000	Stable	Stable	Stable	No
40,000	Stable	+Stable	Stable	No
60,000	-Unstable	+Stable	+Unstable	Yes
80,000	-Unstable	+Stable	+Unstable	Yes
40,000 No Arti. Controller	+Unstable	+Unstable	Stable	No
80,000 No Arti. Controller	-Unstable	+Stable	+Unstable	Yes
(Loaded, 10 KPH, 0.15 Mu)				
28,800	Stable	Stable	Stable	No
57,600	Stable	+Stable	Stable	No
86,400	-Unstable	+Stable	+Unstable	Yes
115,200	-Unstable	+Stable	+Unstable	Yes

Definition of Table 2.8 Terminology

"Stable"	-Little or no change from levels or trends prior to application of drive/brake torque
"+Stable"	-Some increase, of a non-divergent characteristic, from the level prior to application of drive/brake torque
"-Stable"	-Some decrease, of a non-divergent characteristic, from the level prior to application of drive/brake torque
"+Unstable"	-Divergent growth from the level achieved prior to application of drive/brake torque
"-Unstable"	-Divergent reduction from the level achieved prior to application of drive/brake torque

rear-axle wheel spin occurs, provided the articulation hinge controller is employed. Removal of the hinge controller under these conditions causes a lead unit "jackknife" response to occur due to the uncontested destabilizing moment applied to the lead unit from the forward thrust of the trail unit. For runs in which rear-axle wheel spin does occur, "trailer-swing" instability is the result.

2.5 Straight-Line Braking

A few calculations were made for predicting conditions that will lead to wheel lockup at various axles. The method outlined in Appendix D was used in these analyses. The analytical results were verified using the full computerized model. The estimated characteristics (brake torque versus treadle pressure) assumed for each brake on each axle are illustrated in Figure 2.4. The following table lists operating conditions that are predicted to result in wheel lock on various axles.

Approx. Decel. g's	Treadle Pressure psi	Tire/ Road Friction	Bus Full or Empty	Retarder On or Off	Axle Locked Up
0.28	20	0.3	Empty	On	Rear
0.28	22	0.3	Empty	Off	Middle
0.26	32	0.3	Full	On	Rear
0.59	38	0.6	Empty	On	Middle and Rear*
0.50	40	0.6	Empty	Off	Middle
0.47	56	0.6	Full	On	Rear

*Both the middle and rear brakes are on the verge of locking up.

2.6 Control Difficulties in Braking-in-a-Turn Maneuvers

A summary of simulation results, similar to those presented in Section 2.4, are presented in Tables 2.9 and 2.10 that describe the directional stability of the articulated bus following the application of braking. (Appendix B shows the corresponding time histories as Runs #6.1-6.13.) The level of braking used in these runs was based on the straight-line braking results of Section 2.5 and intended to produce

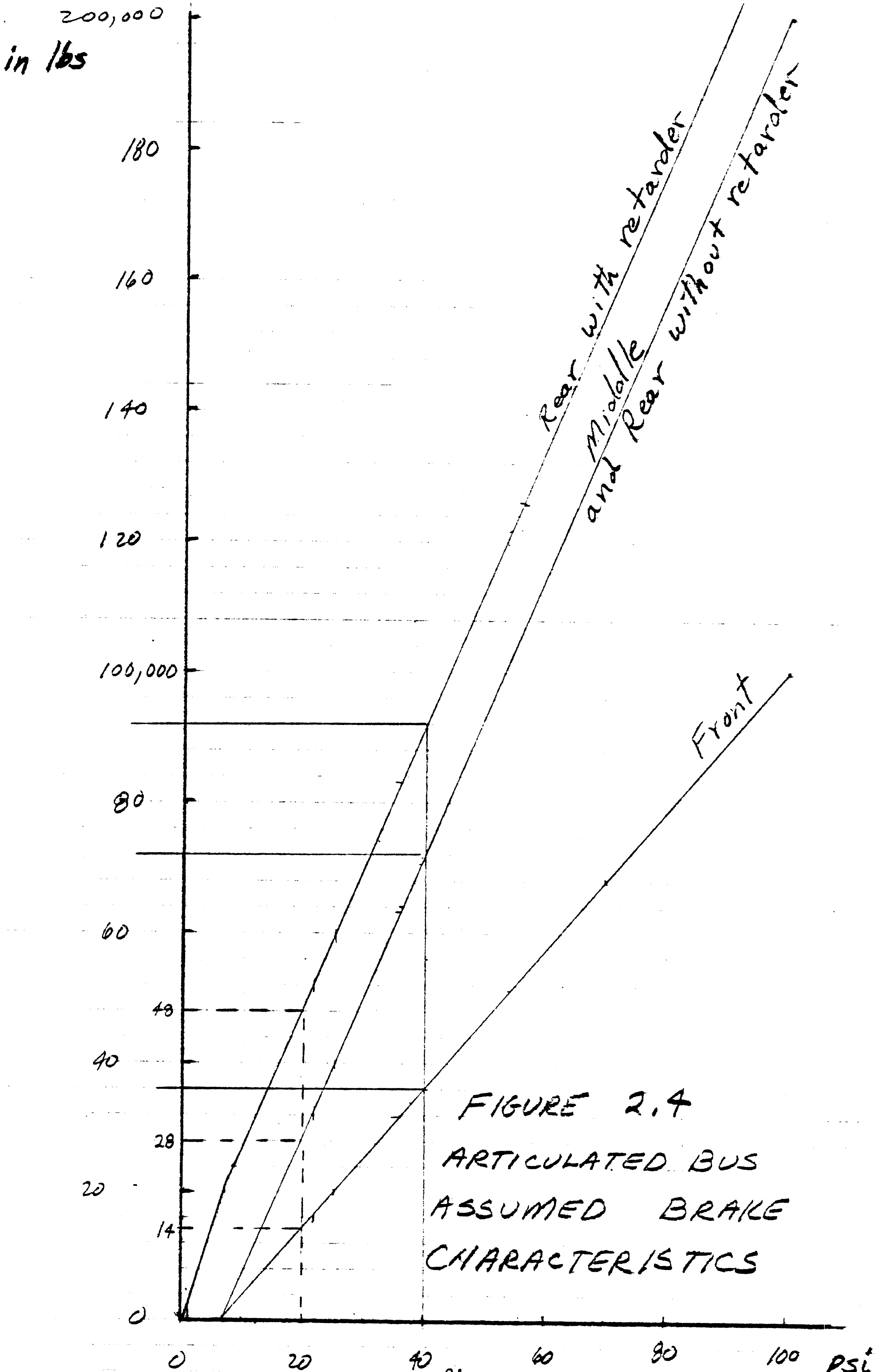


FIGURE 2.4
ARTICULATED BUS
ASSUMED BRAKE
CHARACTERISTICS

Table 2.9. Braking-in-a-Turn Numerics
(Open-Loop)

Simulation Run Description	Articulation Angle Response	Lead Unit Yaw Rate Response	Trail Unit Yaw Rate Response	Wheel Locks	Hinge Controller Able to Limit Articulation Angle Excursion During Instability
Empty, 100 KPH, μ=.6, Run #6.1	+Unstable	+Unstable	Stable	3R, 2R, 1R	Yes
Loaded, 100 KPH μ=.6, Run #6.4	+Unstable	+Unstable	+Unstable	3R, 2R	Yes
Loaded, 100 KPH, No Controller, μ=.6, Run #6.12	+Unstable	+Unstable	+Unstable	3R, 2R	N/A
Loaded, 100 KPH Left Turn, μ=.6, Run #6.13	+Unstable	+Unstable	+Unstable	3L, 2L	Yes
Empty, 50 KPH, μ=.3, Run #6.2	-Unstable	Stable	+Unstable	3R, 3L	Yes
Loaded, 50 KPH, μ=.3, Run #6.5	-Unstable	+Stable	+Unstable	3R, 3L	--
Empty, 50 KPH, No Retarder, μ=.3, Run #6.3	+Unstable	+Unstable	-Stable	2R	Yes
Rmpty, 50 KPH, New Load Data, μ=.3, Run #6.11	+Stable	+Stable	Stable	3R, 2R	--

Table 2.10. Braking-in-a-Turn Numerics
(Closed-Loop)

Simulation Run Description	Articulation Angle Response	Lead Unit Yaw Rate Response	Trail Unit Yaw Rate Response	Wheel Locks	Driver Model Response	Hinge Controller Able to Limit Articulation Angle Excursion During Instability
Empty, 100 KPH, μ=.6, Run #6.6	+Unstable	+Unstable	-Stable	3R, 2R, 2L	Counter-Steer	No
Loaded, 100 KPH, μ=.6, Run #6.9	+Stable	+Stable	Stable	3R, 2R	Counter-Steer	--
Empty, 50 KPH, μ=.3, Run #6.7	-Unstable	Stable	+Unstable	3R, 3L	Counter-Steer	Yes
Loaded, 50 KPH, μ=.3, Run #6.10	-Unstable	-Stable	+Stable	3R, 3L	Counter-Steer	No
Empty, 50 KPH, No Retarder, μ=.3, Run #6.8	+Unstable	-Stable	-Unstable	2R, 2L	Increased Steer	No

some wheel locking in order to challenge the ability of the articulation angle controller to limit any resulting vehicle instability. As is demonstrated in these runs, such items as the manner in which brakes are proportioned, which wheels lock up and their order of lock up, and the nature of the steering-wheel response (e.g., open-loop versus closed-loop), can significantly influence the resulting vehicle response. The variety of braking-in-a-turn responses, that are presented in Appendix B and summarized here, are seen as a reasonable mixture of the kind of directional instabilities that can occur for the examined articulated bus under such operating conditions. These results would therefore seem to present an appropriate set of evidence by which to evaluate the effectiveness of the articulation controller to limit large excursions of articulation angle during such instabilities.

Results of the open-loop simulation runs shown in Table 2.9 fall into two basic categories: (a) those displaying primarily lead-unit "jackknife" instabilities (plus unstable articulation angle responses) on the higher friction surface (μ = 0.6) and (b) those displaying primarily "trailer-swing" instabilities on the lower friction surface (μ = 0.3). These two categories largely reflect the tendency of the vehicle, as proportioned, to lock wheels on (a) the center axle or (b) the rear axle. In each of these runs, the hinge controller was able to limit the articulation angle following the onset of the particular instability. Runs #6.5 and 6.11 did not achieve large enough articulation angles during the simulation run to activate the load-limit feature of the hinge controller. In Runs #6.2 and 6.3, with and without a retarder on the rear axle, the presence of the retarder significantly alters the brake proportioning on the lower friction surface, so as to cause rear-axle lockup and "trailer-swing" instability, in contrast to center-axle lockup and "jackknife" instability without the retarder.

The closed-loop, braking-in-a-turn results, summarized in Table 2.10, differ from those of Table 2.9 in having present during the instability, an active driver model steering response which attempts to steer the lead unit along the prescribed circular path. Column 6 of Table 2.10 describes the general steering behavior of the driver model following the application of braking. The response of the driver model is seen to play an important role in determining whether or not the hinge controller is able to limit large articulation angle excursions. Closer examination of these simulation runs reveals that the countersteer behavior by the driver model can alter the yaw moment (from the open-loop, fixed-steer case) on the lead unit so as to exceed the torque output capability of the hinge controller, thereby preventing the hinge controller from locking the lead and trail units together. However, it is not entirely clear from these results that the best strategy to stabilize the vehicle is simply to prevent large articulation angles. It might be true that under certain conditions, larger increases in articulation angle should be sacrificed in order to help stabilize the directional control of the lead unit. Furthermore, simple corrective counter-steering by a driver may, in some cases, greatly reduce lateral acceleration and yaw rate levels achieved during braking and thereby eliminate the need for the hinge controller to intercede. An example of such a case is given by Run #6.9 and can be compared with the open-loop version, Run #6.4.

Aside from the additional stability that is lent to the lead unit by the corrective counter-steering activity of the driver model, the overall trend of precipitating "jackknife" or "trailer-swing" instabilities is strongly linked, as in the open-loop runs, to which particular wheel combinations lock up during braking.

3.0 RECOMMENDATIONS CONCERNING VEHICLE TESTING

These recommendations contain outlines for six suggested test procedures. The proposed tests have been selected to examine the response of the bus to steering-wheel, brake, and accelerator inputs at various loading conditions, vehicle speeds, and tire/road friction levels. The results of these tests should (1) verify the accuracy of the analytical predictions presented in Section 2.0 and (2) serve to demonstrate the influence of the articulation controller on vehicle performance at the limits of tire/road friction capability.

The thrust of these tests is to develop an overall picture of the maneuvering performance of this unique type of vehicle. The tests, entitled "Turning Response, Ramp-Step Input" (Test #1) and "Straight-Line Braking" (Test #5), are conventional open-loop tests that are often applied to all types of highway vehicles. Test #2 provides a simple means for examining the damping of lateral disturbances of the trailing unit of an articulated vehicle. A pulse input at the steering wheel is chosen to excite a trailer oscillation in Test #2. The ability of a driver to control the articulated bus in lane-change maneuvers that might be required to resolve traffic conflicts is challenged in Test #3. Tests #4 and 6, entitled "Cornering with Acceleration on a Low Friction Surface" and "Braking-in-a-Turn," respectively, have been tailored to exercise the properties of the articulation controller incorporated in the design. Hence, the proposed complement of tests includes both conventional tests that might be applied to a wide range of vehicle types and specialized tests applicable primarily to combination vehicles with (1) an articulation control device and (2) drive thrust applied to the rear axle of the trailing unit.

Since this bus has not been tested previously, maneuvers involving high acceleration levels should be approached with discretion using a process of gradually increasing the severity of the test conditions. Even though the predicted responses obtained from the computerized model do not indicate an unusual propensity for rollover, the possibility that a vehicle may roll over should be guarded against by using the results of previous tests to judge the safety of any new test or any increase in the severity of the maneuver being studied. The numerical order given to these tests (i.e., #1 through #6) reflects the recommended order for enhancing the safety as well as the ease of performing the test program.

The first three tests are structured to study the influences of steering inputs on a good road surface. The level of steering-wheel input used in the ramp-steer test should be gradually increased to achieve maneuvers at specified levels of lateral acceleration. Test results rather than simulation results should be used to set steer levels. Low-speed tests should be performed before high-speed tests. After an understanding of the vehicle's turning properties are obtained from Test #1, then Test #2 can be performed to evaluate the oscillatory tendencies of the directional response of the rear unit. Once the level of stability of the motion of the rear unit has been assessed, enough information will be available to judge the wisdom of attempting a moderately severe lane-change maneuver. With practice in the lane-change maneuver, the driver is expected to become proficient in steering the bus at high speed.

The first reduced friction test proposed is a low-speed cornering maneuver with drive thrust applied. Although not directly related to the straight-line braking and braking-in-a-turn tests, the performance of this test gives the driver experience operating the vehicle on a slippery surface.

The braking tests are believed to be the ones most likely to elicit drastic vehicle responses. The locking of wheels on a single axle may lead to vehicle instabilities that are difficult to control. The directional response of the bus in the straight-line braking test is not expected to be as rapid as in the braking-in-a-turn test, but it may be more unexpected in that the brake pressure causing wheel lock is not known to the driver. Since the brake pressure that will cause wheel lock (and, possibly, the axle on which wheels lock) varies with the frictional level of the tire/road interface, the driver may be surprised if he extrapolates from results on one surface to predict what will happen on another surface. In addition, tests with and without the retarder may yield entirely different types of instabilities on slippery surfaces. In summary, be prepared for unexpected responses in tests involving locked wheels—proceed with caution.

Finally, the fully loaded bus is expected to perform differently than the empty bus. After operating the empty bus, the loaded bus may seem like a new vehicle with its own control requirements. If time and funds permit, the following tests are recommended for both the empty and the fully loaded bus.

3.1 Test #1: Turning Response, Ramp-Step Input

This test provides measures of the steering gain and responsiveness of the vehicle. A test of this type is used by the General Motors Corporation for evaluating passenger cars and it has been proposed to the International Standards Organization as a recommended test for quantifying transient directional response. The yaw rate and lateral acceleration response times are determined from the initial part of the response to a sudden, step-like increase in steering-wheel angle, while the steady turning gain is evaluated after the transient has settled.

For most vehicles (including this bus) the response times and steady-state gain will vary significantly with changes in forward velocity. In addition, vehicle loading will influence the results and nonlinearities in the shear force properties of the tires will cause changes in response characteristics as the level of lateral acceleration is increased. Hence, Test #1, as outlined in Table 3.1, includes a sequence of ramp-step maneuvers at two speeds, three acceleration levels, and two loading conditions.

An extensive instrumentation system is needed to record the variables listed in Table 3.1. Although no attempt is made here to specify the type and quality of the transducers involved, the transducers should be comparable to those used in passenger car work. However, for a complete evaluation, transducers are needed for both the

Table 3.1

Test #1

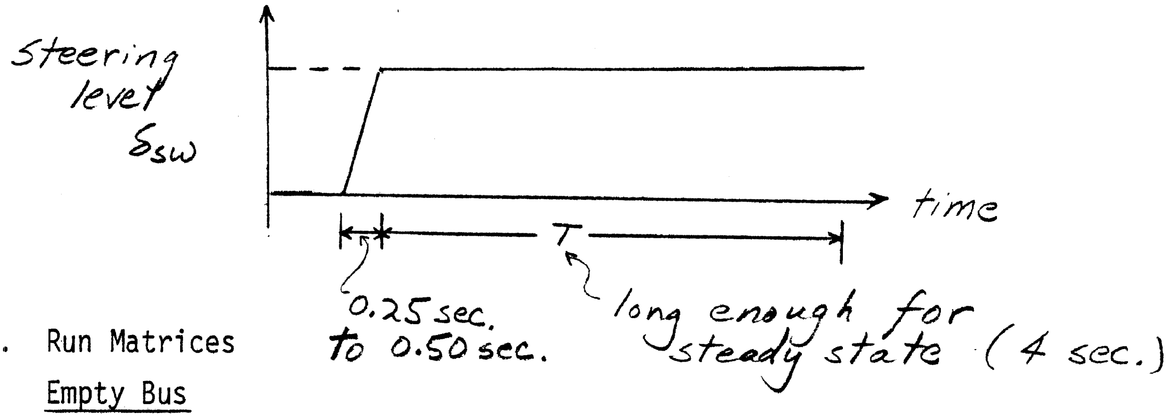
Title: Turning Response, Ramp-Step Input

Description:

A. Inputs

Constant velocities: 50 and 100 Km/hr

Steering Waveform:



B. Run Matrices

Empty Bus

50 Km/hr

1. $A_y = 0.15$ g (δ_{sw} estimate 120°)
2. $A_y = 0.30$ g (δ_{sw} estimate 240°)

100 Km/hr

3. $A_y = 0.15$ g (δ_{sw} estimate 40°)
4. $A_y = 0.30$ g (δ_{sw} estimate 85°)
5. $A_y = 0.45$ g (δ_{sw} estimate 130°)

Loaded Bus

50 Km/hr

6. $A_y = 0.15$ g (δ_{sw} estimate 160°)
7. $A_y = 0.30$ g (δ_{sw} estimate 320°)

100 Km/hr

8. $A_y = 0.15$ g (δ_{sw} estimate 85°)
9. $A_y = 0.30$ g (δ_{sw} estimate 170°)
10. $A_y = 0.45$ g (δ_{sw} estimate 225°)

Watch out for rollover

Table 3.1 (Cont.)

C. Variables Recorded

1. Velocity, V_5
2. Steering-Wheel Angle, δ_{sw}
3. Articulation Angle, Γ
4. Tractor Yaw Rate, r_1
5. Trailer Yaw Rate, r_2
6. Tractor Lateral Acceleration, A_{y1}
7. Trailer Lateral Acceleration, A_{y2}
8. Roll Angle, ϕ

Minimum: δ_{sw}, r_1, V_5, r_2, Γ, A_{y_1}

D. Numerics

-Yaw rate gain

-Articulation angle gain

-Yaw rate response times

-Lateral acceleration response times

-Percentage overshoot

-Oscillation periods

forward and trailing units of articulated vehicles. Judgments as to whether even the "minimum" list of variables fits within available resources may be needed.

The numerics outlined in Table 3.1 correspond to those used in Section 2.1. Figure 3.1 presents calculated results illustrating the measurement of yaw rate numerics from time history information.

3.2 Test #2: Damping of Lateral Disturbances, Pulse-Steer Input

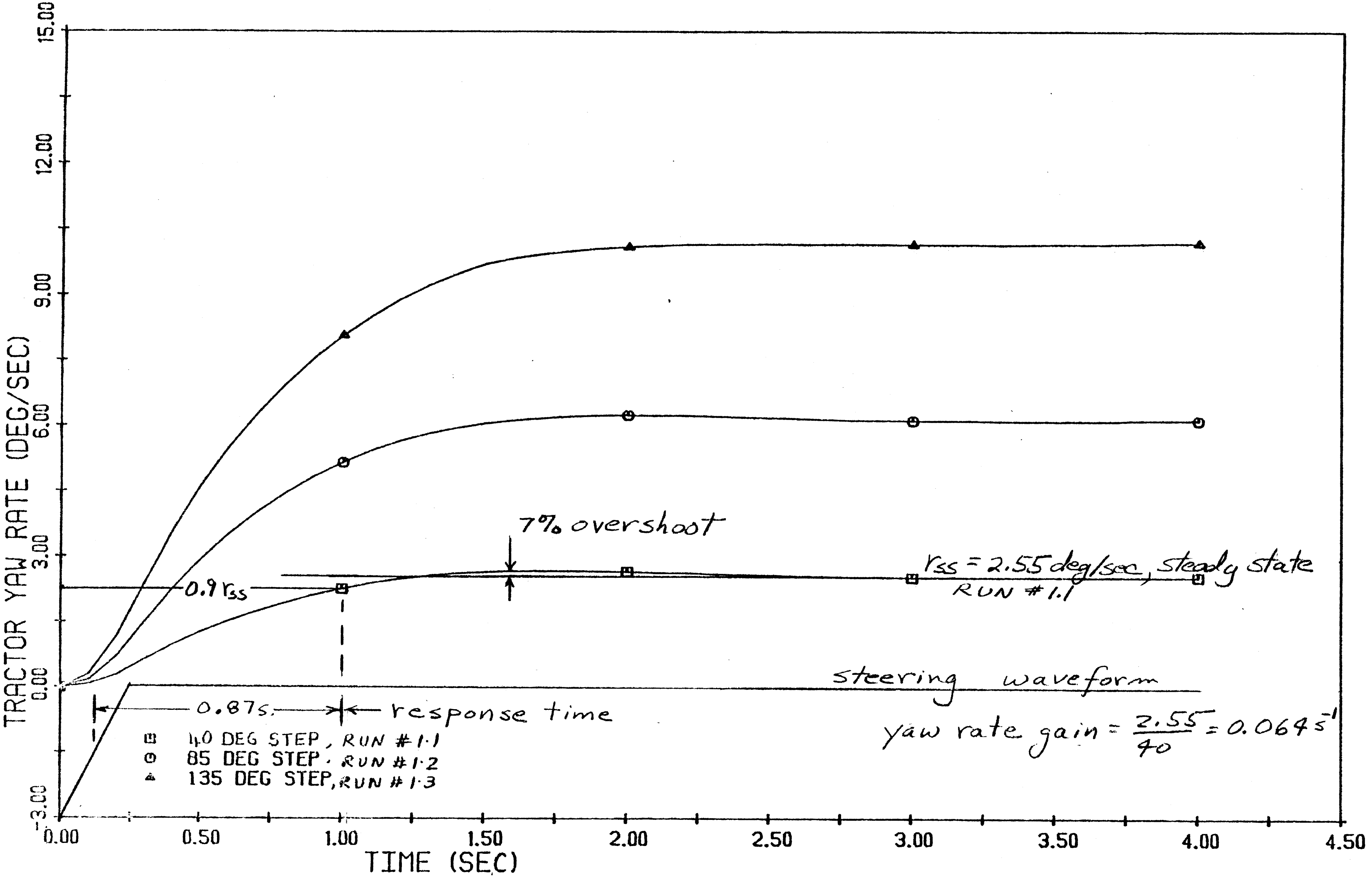
The form of this test corresponds to a type of test that has been recommended to the U.S. National Highway Traffic Safety Administration for evaluating the stability of the trailing units employed in car-trailer or recreational vehicle combinations. The intention of this test is to excite a trailer-swinging oscillation. A "pulse" of steering-wheel input, as proposed for this test, is a very simple means for exciting trailer oscillations. In this maneuver, the ratios of the magnitudes of the excursions of articulation angle and trailer yaw rate and lateral acceleration (see Figure 3.2) provide measures of the damping of the trailer-swinging mode of oscillation.

Table 3.2 presents detailed specifications for Test #2.

3.3 Test #3: High-Speed Lane Change

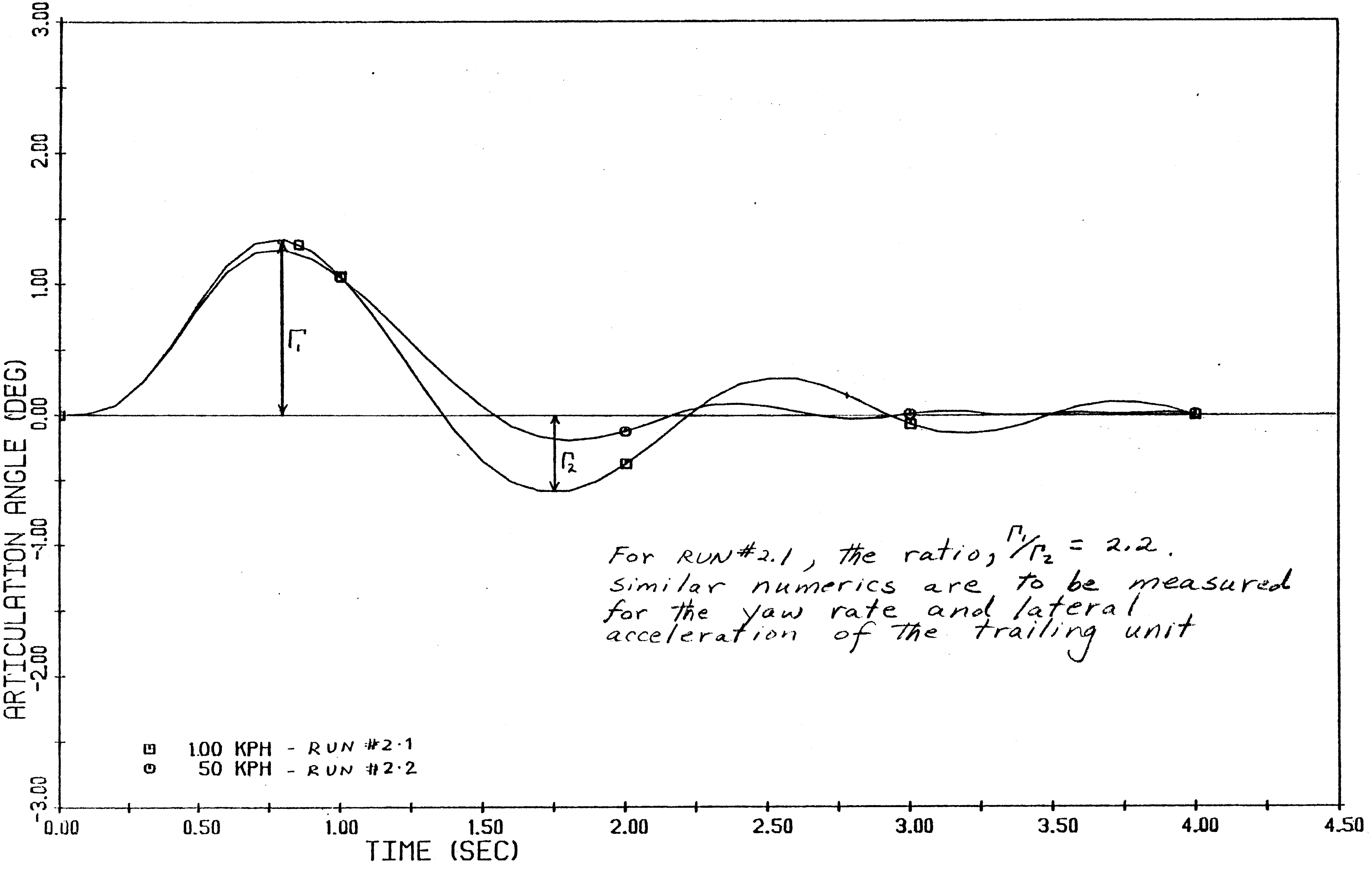
In contrast to Tests #1 and #2, this test requires driver control in following a predetermined path. Although the lateral acceleration and yaw rate response times (as predicted in Section 2.0) for the articulated bus are shorter than those predicted for a standard "straight" bus, the articulated bus is much slower to respond than a passenger car. In order to perform a lane change such as the one described in Table 3.3, calculated results indicate that the driver will need to estimate his trajectory for more than one second into the future. Apparently, drivers of standard buses do learn to provide this much "lead" in their control actions. Nevertheless, Test #3 is intended to challenge the driver's ability to handle the articulated bus in a moderately demanding control task.

11, 12, 13



CANADIAN ARTICULATED BUS, STEP STEER MANEUVERS, EMPTY, 100 KPH,

Figure 3.1



For RUN #2.1, the ratio, $\Gamma_1/\Gamma_2 = 2.2$. similar numerics are to be measured for the yaw rate and lateral acceleration of the trailing unit

CANADIAN ARTICULATED BUS, EMPTY, RESPONSE TO A PULSE STEER INPUT

Figure 3.2

Table 3.2

Test #2

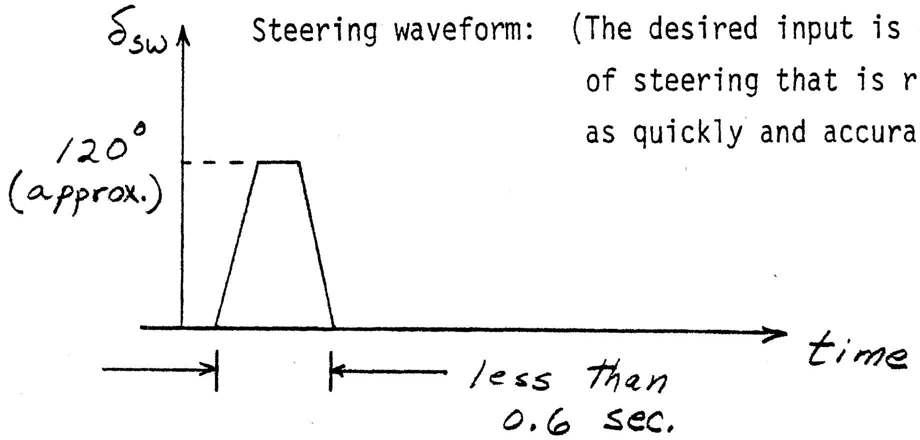
Title: Damping of a Lateral Disturbance, Pulse Steering Input

Description:

A. Inputs

Constant velocities: 50 and 100 Km/hr

Steering waveform: (The desired input is a rapid pulse of steering that is returned to zero as quickly and accurately as possible)



B. Run Matrix

Empty

1. 50 Km/hr
2. 100 Km/hr

Loaded

3. 50 Km/hr
4. 100 Km/hr

C. Variables Recorded

Same as Test #1

D. Numerics

-Ratios of first to second peaks of r_2, Γ, and A_{y2}

-Time between peaks

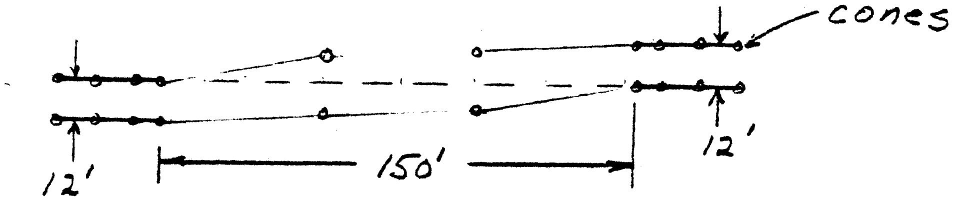
Table 3.3

Test #3

Title: High-Speed Lane Change

Description:

A. Inputs: Desired vehicle path. (This is a closed-loop test performed with driver control. The driver should practice at lower speeds, attempting to reach 100 Km/hr after "learning" the maneuver.)



B. Run Matrix

Loaded and empty at 100 Km/hr

C. Variables Recorded

Same as Test #1

D. Numerics

-Lane exceedances (cone strikes)

-Driver opinions

-Analysis of steering waveforms, ratios amongst first, second, and third peaks

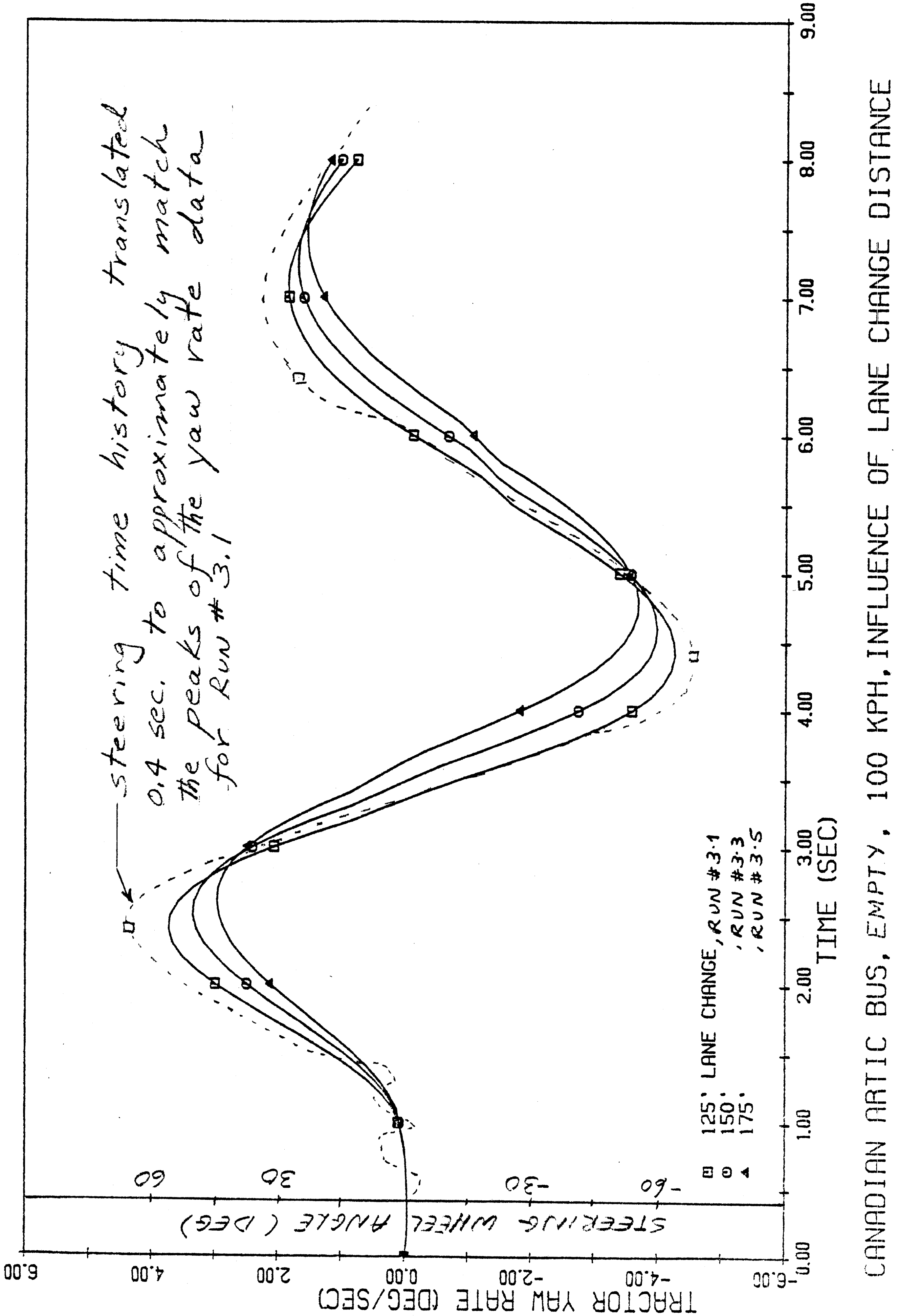
-Cross-correlation lags (time intervals between maximums and minimums of inputs and responses), e.g., δ_{sw} to A_{y1}, r_1, A_{y2}, r_2, Γ and Γ to r_2 and A_{y2}. These cross-correlation lags are open-loop measures in that they evaluate the forward loop (i.e., the vehicle) in the closed-loop driver-vehicle system.

Experience on the test facility may indicate that the lane change specified in Table 3.3 is either too mild or too severe. The experimenter may want to consider modifying the geometry of the predetermined path based upon test results and driver reactions.

The numerics suggested in Table 3.3 include (1) subjective opinions, (2) closed-loop numerics such as the number of cone strikes and the number and magnitude of major steering reversals, and (3) cross-correlation measures of the lags between input and output quantities. Figure 3.3 illustrates how test data may be processed graphically to obtain those numerics that can be estimated from time history information. For successful lane-change maneuvers, experience in vehicle testing has shown that the yaw rate and lateral acceleration waveforms are almost the same shape as (i.e., closely correlated to) the time history of steering-wheel input. The primary differences between the steering input and the yaw rate and acceleration outputs are the time delays associated with the response time of the vehicle in this maneuver. Estimates of the lengths of these time delays are a means for assessing the responsiveness of the vehicle in an emergency maneuver that might be performed on the highway.

3.4 Test #4: Cornering with Acceleration on a Low-Friction Surface

This test addresses problems related to applying drive thrust to the wheels on the rear-most axle of the articulated bus. If the road surface is slippery and the vehicle is attempting a right-angle turn, the presence of drive thrust might tend to either (1) jackknife the vehicle or (2) cause the trailing unit to swing out into an adjacent lane. The predictions presented in Section 2.4 indicate that under certain operating conditions, the trailing unit of the bus will swing outside of the turn when the drive thrust is sufficient to spin the rear wheels of the vehicle. The outline of Test #4 (see Table 3.4) gives instructions for attempting to duplicate these hazardous operating conditions.



CANADIAN ARTIC BUS, EMPTY, 100 KPH, INFLUENCE OF LANE CHANGE DISTANCE

Figure 3.3

Table 3.4

Test #4

Title: Cornering with Acceleration on a Low Friction Surface

Description:

A. Inputs:
  (1) tire/road friction ≈ 0.15
  (2) initial velocity: 7 mph (10 ft/sec)
  (3) steering input: for a tight turn (something like 30° at the front wheels or about 1000° at the steering wheel)
  (4) accelerator inputs: low, intermediate, and high

B. Run Matrix:

Loaded and empty for 3 levels of accelerator input—a total of 6 runs

Special Instructions: Drive into the turn for approximately 4 seconds then apply the accelerator. The highest level of accelerator input should be sufficient to spin the rear wheels.

C. Variables Recorded

δ_{sw}, V_5, Γ, r_1, r_2, A_{y1}, A_{y2}, A_{x2}

Minimum: V, Γ, r_1

Extra: ω_3, speed of the rear wheels
δ_a, accelerator position

D. Numerics

- Articulation angle (Γ) change after thrust is applied
- Off-tracking of the rear unit with respect to the lead unit

3.5 Test #5: Straight-Line Braking

The braking capability of any vehicle is of interest. However, an additional purpose of this test is to provide information for use in Test #6. The desired information consists of (1) the pressure levels that will cause wheel lock on various test surfaces and (2) knowledge of which wheels lock up under various operating conditions.

Although straight-line braking tests are conceptually simple, practical matters can cause difficulties in obtaining meaningful results. The brakes need to be burnished to a reasonable extent. The torque capabilities of heavy vehicle brakes of nominally the same type may differ considerably. Furthermore, these brakes may require special care to obtain proper adjustment. None of these matters is addressed in the outline provided in Table 3.5. In this case, we have assumed that the experimenters have their own procedures for conducting braking tests.

Table 3.5 primarily provides guidance as to the operating condition wanted. Clearly, various friction levels are not easily supplied, so the tests will have to be conducted on the surfaces available. However, the frictional characteristics of the surfaces used for the straight-line braking tests should be relatable to (or the same as) the frictional characteristics of the surfaces employed in the braking-in-a-turn tests.

Careful attention should be paid to any directional responses or instabilities that occur during Test #5. If wheels lock, severe directional responses might ensue. Any unstable tendencies should be noted for use in guiding the conduct of Test #6.

3.6 Test #6: Braking-in-a-Turn

In this study, the purpose of recommending braking-in-a-turn tests is to excite directional instabilities of sufficient magnitude to exercise the limiting properties of the articulation angle controller.

For this test, the experimenters may have to exercise considerable judgment in finding test conditions and operating procedures that are

Table 3.5

Test #5

Title: Straight-Line Braking

Description:

A. Inputs: (1) initial velocities: 50 and 100 Km/hr *

(2) tire/road friction: $\mu = 0.1$, 0.3, and 0.6

(3) steering input: $\delta_{sw} = 0$ (vehicle may turn slightly to the right)

(4) various treadle pressures, P_B

B. Run Matrix

Attempt to establish the level of brake pressure for lock up on $\mu = 0.3$ and 0.6 surfaces for the loaded and empty vehicle with and without the retarder turned on.

On the $0.1 = \mu$ surface see if the retarder will lock the rear wheels. (The retarder is most effective when the retarder is cold.)

C. Variables Recorded

V, P_B, A_{x1}, r_1, Γ, θ_1 (pitch angle), ω_1, ω_2, ω_3 (wheel speeds)

D. Numerics

Wheels unlocked stopping distance or deceleration level

---

* For 100 Km/hr., tests on a surface with $\mu \leq 0.3$ may be impractical and/or dangerous.

both useful and safe. Table 3.6 provides guidance based on a limited number of calculations (see Appendix B, Section B.6). However, a wide variety of directional responses is possible, depending upon which wheels lock and in what order. Appropriate combinations of pressures and surfaces will probably have to be identified during the testing operation.

Test #6, as defined in Table 3.6, has been divided into two parts for safety reasons. The results obtained at an initial velocity of 50 Km/hr on a path of approximately 430-foot radius with a surface friction of $\mu_{peak} \approx 0.3$ may be sufficiently dramatic to preclude tests starting at 100 Km/hr on a high-friction surface. Nevertheless, if deemed safe to perform, the high-speed, high-friction case has a real world analog in decelerating rapidly on a freeway exit ramp entered at the speed limit. In both parts of Test #6, the results from Test #5 are to be used in selecting brake pressure levels that will cause wheels to lock. Nevertheless, the driver should exercise caution and perform tests below locked-wheel values of brake pressure before attempting locked-wheel runs.

Table 3.6

Test #6

Title: Braking in a Turn

Description:

Part 1

A. Inputs

Surface: $\mu_{peak} \approx 0.3$

At 50 Km/hr (45.6 ft/sec), travel on a path of radius $R \approx 430$ ft (about 0.15 g) for approximately 3 seconds before applying the brakes.

B. Run Matrix

For $\mu_{peak} \approx 0.3$, the empty vehicle with the retarder in use should lock wheels at the rear axle at a brake pressure, P_B, of about 22 psi, if the estimated brake torques used in the simulation are accurate. In any event, the straight-line braking tests should indicate the P_B value for wheel lock. Make a run at wheel lock. (This may be violent and bring the articulation angle limiter into use.)

Make another test without the retarder in use. The middle axle should lock for the empty vehicle at $P_B \approx 25$ psi. A violent jackknife may start until the articulation angle limiter takes over.

Make a third test for the loaded vehicle with the retarder in use on the 0.3 surface. The rear wheels should lock for $P_B \approx$ psi.

This maneuver can be run both open- and closed-loop. In the open-loop version, the driver holds the steering fixed after the brakes are applied.

C. Variables Recorded

$V, P_B, A_{x1}, r_1, r_2, \Gamma, A_{y1}, A_{y2}$

$\omega_1, \omega_2, \omega_3, \theta, \phi, \delta_{sw}$

Table 3.6 (Cont.)

D. Numerics

1. Open Loop
   - changes from steady turn values for r_1, r_2, Γ, A_{y1}, A_{y2}
   - path deviations
2. Closed Loop
   - path deviations (cone strikes)
   - steering activity
   - braking activity (if allowed)
3. Articulation controller performance
   - maximum articulation angle

<u>Part 2</u>

A. Inputs

Surface: $\mu_{peak} \simeq 0.6$

At 100 Km/hr, travel on a path of radius $R \approx 1720$ ft (a 0.15 g turn). Travel on the path for 3 seconds to establish a steady turn, then apply the brakes.

B. Run Matrix

Be careful not to rollover. Work up to a lockup braking level only if it is safe.

For $\mu = 0.6$ and at $P_B = 63$ psi for the loaded vehicle, rear wheels should lock up at $P_B = 44$ psi for the empty vehicle.

These maneuvers can be run both open- and closed-loop. In the open-loop version, the driver holds the steering fixed after the brakes are applied.

C. Variables Recorded

Same as Part 1

D. Numerics

Same as Part 1

4.0 CONCLUDING STATEMENTS

The calculated results obtained in this study provide a comprehensive prediction of the directional response properties of the articulated bus. The following listing summarizes the principal results for (1) steady turning performance, (2) directional response time in sudden turns, and (3) damping of trailing unit oscillations:

- Steady Turning

  Lead unit understeer:
    empty 4 deg/g
    full 10 deg/g

  Steering gain:
    empty at 100 Km/hr, 0.35 g per 100° of steering-wheel angle

    full at 50 Km/hr, 0.09 g per 100° of steering-wheel angle

  Articulation angle sensitivity to lateral acceleration:
    empty -0.1 deg/g

    full - 0.8 deg/g

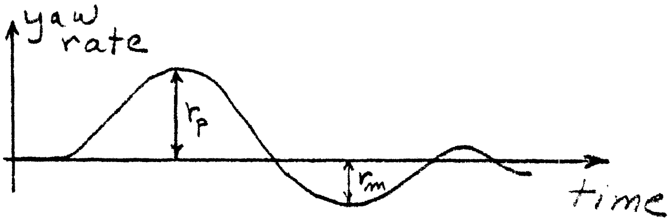
- Ramp/Step Steer (approximately 0.15 g steady state)

  90% response time for the yaw rate of the lead unit at 100 Km/hr:
    empty 0.9 sec
    full 0.6 sec

- Pulse Steer

  Oscillation reduction factor for the yaw rate of the trailing unit at 100 Km/hr:

  (Reduction factor = r_p/r_m)

    empty 2.9
    full 2.0

The steady turning results listed above indicate a wide range of steering gain depending upon vehicle speed and loading condition. This finding is to be expected for a vehicle with the understeer levels predicted for this bus. An example calculation for a typical straight bus with dimensions corresponding to the forward unit of the articulated bus yields an understeer value of 2 deg/g when the straight bus is empty. Hence, the steering gain of the articulated bus is predicted to be noticeably less than that of a comparable straight bus.

However, the predicted yaw rate response time (0.9 sec) for the articulated bus is faster than the response time of 1.1 sec estimated for a comparable straight bus. These response times are much longer than passenger car response times (i.e., approximately 0.2 sec). Nevertheless, the findings for both steering gain and response time appear to indicate that the handling qualities of the articulated bus will be similar to those achieved by straight buses in turning maneuvers typical of normal driving.

Since the subject bus is articulated, the turning performance of the trailing unit needs to be examined. With regard to steady turns, the articulation angle is predicted to be largely independent of lateral acceleration (the influence being less than 1 degree of articulation angle per "g" of lateral acceleration). Hence, the trailing unit is expected to track a desired curve with an articulation angle that is nearly proportional to path curvature. In other words, the tracking of the trailing unit is predicted to be good in steady turns at roadway speeds.

Combination vehicles with the hitch point located behind the rear axle of the lead unit tend to exhibit lightly damped yaw oscillations of the trailing unit. The results obtained for the articulated bus indicate the presence of trailer swinging in response to a pulse of steering-wheel input. In the worst case studied, the amplitude of the yaw oscillation of the trailing unit is decreased by at least 50 percent during the first half cycle of the oscillation. In regard to this oscillation, the damping provided by the articulation controller helps, but it is not large enough to have a major influence. The distribution of weight in the trailing unit is important. The damping of the yaw oscillation of the trailing unit will be reduced from the level predicted by the simulation if the actual load distribution results in the location of the center of gravity of the trailing unit being closer to the rear axle than the value used in the computerized model. In contrast to the predicted behavior of the articulated bus, a typical commercial tractor-semitrailer will have a heavily damped yaw response of the semitrailer. Nevertheless, the damping of the yawing motion of the trailing unit of this bus appears to be large enough to prevent troublesome lightly damped oscillations from persisting for many seconds as can happen for some car-trailer combinations.

In addition to the above findings concerning the basic nature of the directional response to steering, certain matters related to control difficulties and potential accident situations were pursued in this study. The specific situations addressed were (1) sudden lane changes to resolve traffic conflicts, (2) accelerating in a turn on a slippery surface, and (3) severe braking (relative to the frictional potential of the tire/road interface) during a turn.

Since the bus is slow to respond, the ability of drivers to avoid obstacles by sudden steering maneuvers (e.g., a rapid lane change) may be somewhat limited. Based on calculated results for traveling at 100 Km/hr, a driver that is "looking" at least 1.5 seconds ahead should be able to change lanes successfully (without an undue amount of trailer swinging or other undesirable response) thereby avoiding the obstacle. Presumably, this is the type of performance that drivers of straight buses have learned to use with acceptable results.

A unique feature of this articulated bus is that the rearmost axle is driven. In this sense, the articulated bus differs from almost all other combination vehicles. Due to the presence of drive thrust at the rear axle, tires on the trailing unit may experience reduced side force capability during acceleration. If the rear wheels begin to spin on a slippery surface, the rear unit of the vehicle will straighten out with respect to the front unit. In this case, the rear unit may strike adjacent vehicles. This behavior may be something that bus drivers will need to be aware of in order to prevent low-speed accidents when turning at icy street corners. It is worth noting that the force developed by the articulation controller will tend to increase the rate at which the rear unit straightens out during acceleration in a turn on a slippery surface. However, the same basic phenomenon (straightening out) will occur if the articulation controller is completely disabled.

Not surprisingly, the articulated bus is directionally unstable in braking-in-a-turn maneuvers at braking levels sufficient to cause wheel lockups on the rear or middle axle. (Almost all highway vehicles are unstable if wheels lock on axles other than the front axle.) However, predicted results for braking-in-a-turn maneuvers provide the means for examining the performance of the articulation controller in preventing the bus from "folding up." Based on the predicted results, the controller has sufficient torque capability to limit the articulation angle to a preset value of approximately 8 degrees if the driver does not steer to try to regain the originally intended path. Interestingly, if the driver does steer to attempt to achieve the desired path, there are cases in which the simulated values of the maximum torque capability of the articulation controller are not large enough to limit the articulation angle to 8 degrees. In practice, the driver's control actions are very difficult to predict when the vehicle is essentially out of control. Possibly, the driver will attempt to modulate the braking level to eliminate wheel lock. In that case, the fact that the articulation controller prevents or significantly reduces the tendency for the articulation angle to grow beyond reasonable bounds may provide the driver with an opportunity to regain directional control. The driver would not have had this opportunity if a rapid jackknife or a large unobserved trailer swing had occurred.

Incidentally, in establishing braking levels that would cause wheel lock, the performance of the bus with and without a retarder was examined. The basic observation resulting from this examination is that the brake proportioning (front to rear) is better when the retarder torque is present. Without the retarder, the middle axle of the vehicle will lock up considerably before the other axles do, thereby causing the vehicle to have a strong jackknifing tendency.

Although the predictions presented in this report are based on a comprehensive vehicle model, they are to be viewed as guides for developing plans for testing the prototype bus. Certain critical vehicle parameters were not known exactly. Accordingly, estimated values were used in the computerized model. In particular, the steady turning results (understeer, etc.) are highly dependent upon the compliance in the steering system. The distribution of mass and the c.g. location for the trailing unit may differ between the prototype vehicle and the simulated bus. Hence, the swinging tendency of the trailing unit may be under- or over-estimated in the predicted results. Parametric values associated with the articulation controller were based on calculations—not component tests. Possibly, the representation of the controller may not be completely correct. Furthermore, the torque capabilities of the installed brakes may not be very close to those estimated. Obviously, accurate predictions of vehicle performance depend upon obtaining accurate data describing the vehicle. Nevertheless, the predicted results are very useful in that they provide a foundation for determining if vehicle tests are yielding results that are either explainable or unexpected.

The test procedures recommended in Section 3.0 are structured to allow the experimenters to make maximum use of the predicted results obtained in this study. In this regard, the understanding and experience gained by HSRI in simulating the vehicle could be used to MTC's advantage if HSRI were to participate in the testing of this bus.

REFERENCES

1. MacAdam, C.C., Fancher, P.S., Hu, G.T., and Gillespie, T.D. "A Computerized Model for Simulating the Braking and Steering Dynamics of Trucks, Tractor-Semitrailers, Doubles, and Triples Combinations. User's Manual - PHASE 4." MVMA Project 1197, Highway Safety Research Institute, University of Michigan, Report #UM-HSRI-80-58, September 1980.

2. Ervin, R.D., et al. "The Yaw Stability of Tractor-Semitrailers During Cornering." Final Report, Contract DOT-HS-7-01602, Highway Safety Research Institute, University of Michigan Report #UM-HSRI-79-21, June 1979.

3. Proposal Response to RFP No. 523-8, "Measurement of Pavement-Truck Interaction Under Experimental Conditions." Submitted to Federal Highway Administration by Highway Safety Research Institute, University of Michigan, October 10, 1978. (Contract No. FH-11-9577)