THE UNIVERSITY OF MANITOBA

# WIND DRIVEN INSTABILITY OF TRACTOR-TRAILER COMBINATIONS

BY

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ABSTRACT

An investigation into the literature on vortex streets shed by blunt objects subjected to wind showed that the periodicity of the vortex and its strength are related to blunt body (i.e. trailer) motion in yaw as well as to angle of attack and magnitude of wind. These factors were modelled in a program on an IBM-PC and coupled with suspension system behavior to produce a non-linear second order differential equation describing trailer yaw. By introducing a random number generator to simulate wind gusts, and compiling information on tractor-trailer geometry and suspensions, a computer model with graphics capability was developed. The output of yaw as a function of vehicle speed, wind velocity and attack angle, wind variance, and trailer suspension behavior is plotted as a function of time. This model, much more simple than the University of Michigan models, appears to describe reasonably well the qualitative behavior of a tractor-single trailer in yaw. In consultations with local carriers, the predicted output from the PC model were very realistic. This paper represents the culmination of this work.

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## NOMENCLATURE

$I_{zz}$ = Trailer moment of inertia about the kingpin

$\ddot{\theta}$ = Lateral yaw acceleration of trailer

$\sum_{1}^{5} M$ = Summation of moments about kingpin

$M_1$ = Frontal aerodynamic moment

$M_2$ = Lateral wind moment

$M_3$ = Lateral tire/road friction moment

$M_4$ = Suspension moment

$M_5$ = Vortex shedding moment

$L_1$ = Moment arm to center of area

$\rho$ = Air density

$A$ = Effective area

$\cos\theta, \sin\theta$ = Cosine and sine of yaw angle theta.

$V_F$ = Vehicle velocity (Frontal wind velocity)

$V_W$ = Crosswind velocity

$C_D$ = Co-efficient of drag.

$\mu$ = Co-efficient of tire/road friction

$N$ = Weight of trailer (lb-force) at rear tandems

$L_2$ = Distance from center of force to kingpin

$\dot{\theta}$ = Yaw velocity (radians/unit time)

$K$ = Suspension spring constant (lb-force)

$S$ = Distance from suspension roll center to spring center (ft.)

$h_2$ = Distance from suspension roll center to center of suspended mass (ft.)

$M$ = Sprung mass of trailer

$D$ = Trailer width

# WIND DRIVEN INSTABILITY OF TRACTOR-TRAILER COMBINATIONS THEORIES BASED ON COMPUTER MODELLING AND ON-SCENE ANALYSIS

## INTRODUCTION

The vast majority of highway safety research to date has focused on improving passenger vehicles. One class of vehicle which has been overlooked by safety agencies until recently is the articulated commercial vehicle. There are several reasons for overlooking articulated vehicles. Tractor-trailers do not account for a large percentage of accident statistics, they are not utilized for transporting passengers, and they account for a small percentage of the registered vehicle population. However, their involvment in accidents represents a significant commercial loss and often a cost in human life.

Although large vehicle safety has always been of concern to highway agencies, this issue is rapidly approaching the forefront of research. This enhanced attention is a natural consequence of several factors. Firstly, many highway agencies in the United States and Canada have relaxed entry and operational (in addition to weight and dimension) constraints. This has led to a proliferation of larger and different tractor-trailer combinations operating on our roadways. Secondly, tractor-trailers are employed, in increasing numbers, for hauling hazardous materials. When a commercial vehicle laden with toxic materials is involved in a collision, it can draw considerable negative media attention to the trucking firm, even when the risk to the community is minimal. A third concern stems from the downsizing of passenger vehicles coupled with the increase in size and length of of trucks. This combination of changes is perceived by many to to be a negative development. That being said, truck safety issues have been a hotly debated topic, particularly between automobile and trucking associations. In many cases, the issues are prejudged by emotions rather than applying a logical, scientific approach.

The most commonly utilized method of evaluating vehicle safety is an analysis of the accident experience of the vehicle type in question. Although this method has proven useful in assessing the overall scenario, it fails to address such issues as what are the particular combination of vehicle, road, and environmental factors which are prevalent in particular classes of accidents and why they occur together. Obviously, overwhelming evidence such as equipment malfunctions, driver fatigue, or load loss are easily identified while subtle factors such as inherent vehicle instability may be masked or misclassified. The application of multivariate statistical analysis techniques[1,2] has improved the deductive process considerably. But fundamental questions such as what initiates (or perpetuates) a vehicle into an unstable mode and what are the most economical ways to improve safety without creating an economic burden on society or industry remain unanswered. In contrast, the emergence of complex computer techniques [3,4] have been successfully applied in evaluating vehicular characteristics. However, the level of mathematical sophistication has a tendency to overwhelm the reader and, if improperly employed, yields erroneous results.

In the fall of 1985, the University of Manitoba initiated a small, part-time study to assess the feasability of conducting heavy vehicle collision research in the Province of Manitoba. During the course of data collection it had become apparent that wind driven instability of articulated vehicles was a factor in driver loss of control. These accidents were previously designated as "loss of control" or "jacknife" without further clarification. Indeed, the accidents were tacitly assumed to be the driver's fault. Our investigation of wind records indicate that these accidents occurred most often during periods when the wind velocity was at or greater than a particular magnitude. The cause of loss of control seemed to lie in a dynamic interaction of the wind, forward speed of the vehicle, and the suspension system of the trailer.

The objective of this thesis is to analyze the data gathered from articulated accidents using multivariate analysis and to develop a mathematical model of dynamic behavior of articulated vehicles to determine the nature of articulated vehicle inherent instability.

# CHAPTER 2: LITERATURE REVIEW

## 2:1 VORTEX SHEDDING OF BLUFF BODIES

A tractor-trailer travelling down a highway can generate considerable aerodynamic forces so that a major portion of operating costs go toward overcoming the retarding forces of wind drag. In an effort to conserve fuel, carriers have adopted such drag reduction devices as tractor-cab mounted deflectors, bulbous noses on trailers, and innovative tractor designs. Yet for all intents and purposes, a highway rig can still be considered analogous to a large blunt edged three-dimensional body moving freely in an air stream. As a consequence of this configuration, these vehicles produce a phenomenon known as vortex shedding (Figure A1). Passenger vehicles experience the results of this effect when following rigs down the highway as the passenger vehicle is pitched from side to side. During rain or snow storms the vortices can be noted visually. Considerable research has been conducted on the phenomenon of vortex (or wake) shedding [6-19]. However, the majority of this work is not directly applicable to the problem at hand. Despite this, inferences can still be drawn from the work of Wood [20], Komatsu and Kobayashi [21], Shiraishi and Matsumoto [22], and Olivari [23], in the development of theory and model.

The latter portion of Wood's work focuses on tank observations of a heaving airfoil. A trailer pivoting about the king-pin would be subjected to similar formation mechanisms at the trailing edge. Wood noted that for a sharp-edged airfoil, the ensuing wake developed a clock-wise motion about the trailing edge, thus forming a "thrust-type" vortex trail with downstream velocity. Whereas, for a blunt-edged airfoil, the vortex is captured close to the base and is carried across the wake where it is finally displaced by the next vortex. The result is a "drag-type" trail with a 90-180 degree phase lag with an upstream velocity (Figure A1). Wood assumes that this is simply a displacement effect of the blunt edge and that increasing the heaving amplitude would restore the thrust type trail. After conducting further tests, the result was an increase in both strength and spacing of the ensuing vortex action. Oscillations are thus associated with periodic crossflow, and hence fluctuating lift, incidence, and circulation. Transverse oscillatory motion will be positively damped if the lift component remains in phase with the incidence and opposes the direction of lateral motion. Wood stated that for excitation, a phase shift greater than or equal to 90 degrees is necessary to provide a component in phase with the velocity.

Referring to Figure A2, Wood makes the following explanation: for a conventional airfoil virtual mass effects cause the lift to be dependent on acceleration rather than transverse velocity. In addition, there is a lift component proportional to and in phase with the circulation.

For a blunt base, Wood assumes that the virtual mass component is unaffected. Thus the circulation component is not only rotated because of the phase lag, but the magnitude increases as well. The vector representing the circulation component of lift is sufficiently large enough to sweep the resultant lift vector into the second quadrant where it has a significant component in phase with the motion. Therefore, a sharp edged airfoil requires external force to sustain lateral oscillation while a blunt-edged airfoil has a mechanism to extract energy from the flow to perpetuate oscillations. Thus a possible aerodynamic mechanism to drive articulated vehicle oscillation definitely exists.

Komatsu and Kobayashi[21] and Shiraishi and Matsumoto[22] examine motion-induced shedding of bluff bodies with the latter concentrating on the application for bridge structures. Komatsu and Kobayashi conclude that there are two mechanisms which are potentially responsible for formation of vortex streets. The first is restricted to oscillations of small amplitude caused by Karman vortex shedding [6-19] having a separation point at the trailing edge. The second mechanism, which is independent of Karman shedding, has a separation point at the leading edge with a large amplitude.

They further observe that a fluctuating pressure distribution along the chord of the body is produced by the second category of vortex shedding and is attributable to motion induced oscillations. They further argue that Karman vortex shedding may be an initiation mechanism for motion induced shedding.

Referring to Figure A3, Komatsu and Kobayashi offer the following supposition:

(1)The generation of the vortex from the leading edge A synchronizes with the oscillation of the body.

(2)The vortex keeps growing during the cycle.

(3)The vortex is shed from the trailing edge E into the wake. The vortex built up at the lower edge A′ behaves in the same manner as described above. The curvature of the streamlines over the vortex is accompanied by a reduction of pressure at the adjacent part of the surface.

(4)The developed vortex D shown in Figure A3(iv) produces an upward lift which must be greater than the downward lift due to vortex B′. Thus the total lift-force acts upward and synchronizes with the upward movement of the body itself. The reverse situation is produced by vortices D′ and B before or after a half-cycle, as shown in Figure A3(ii). The interaction between vortex-induced force and the body motion is repeated in every cycle of oscillation. Thus the body is subjected to an in-phase exciting force produced by the vortices and the oscillation is maintained steadily.

Shiraishi and Matsumoto conducted a series of tests to examine the effect of various bluff body geometries on vortex shedding characteristics. Two of the geometries considered were blunt trailing edged bodies with and without a bulbous lead edge. Inferences can be drawn to adopt the work in analyzing the effect of wind deflectors on trailers. The results for a blunt lead and trailing edged body (i.e. a trailer) corroberates the findings of Komatsu and Kobayashi[21]. Shiraishi and Matsumoto[22] obtained induced vortex shedding from the lead and trailing edges and attribute them to a fluctuating pressure difference along the chord of the body, whereas vortices shed from a bulbous leading edged body tended not only to be suppressed, but also improved flow control at the trailing edge. The reduction is attributed to an decrease in the magnitude of pressure variation coupled with an increase in the phase lag of greater than 180 degrees.

It is noted that the above works are for laminar flows with low reynolds numbers, whereas a trailer oscillating in wind can experience considerable turbulent flow. However, from the literature reviewed, and utilizing Figure A4, it is seen that a fluctuating pressure differential is developed on the leeward side of the trailer with a simultaneously occurring destabilizing moment about the kingpin. The resultant wind force angle and magnitude is directly proportional to the square of the sidewind velocity. Thus despite the difference in flow types, the principle formation and driving mechanisms are present for the articulated vehicle.

## 2:2 SUSPENSION EFFECTS

Ervin [24] notes the trailer suspension characteristics as they relate to vehicle stability. The roll motion of the sprung mass on the suspension rotates about the suspension roll center. The suspension components, axle(s), and tires rotate about the tire roll center in the ground plane as the tires deflect due to left/right load transfer. For typical heavy vehicles, 2/3 of the total roll angle subtended by the sprung mass involves rotation about the suspension roll center while the remaining 1/3 rotates about the tire roll center. Since the majority of roll motion is about the suspension roll center, it is important to note that the lateral destabilizing moment (M1*Ay*H2), as seen in Figure A5, is proportional to the lever arm H2, between the sprung mass center and suspension roll center. Suspensions on most North American trailers have a suspension roll center height of 22 to 30 inches above the ground.

Ervin assumes a rigid model in the above narrative which is acceptable as an initial approximation. However, a more accurate description would be the following. The moment produced by the suspended mass is approximated by M1*Ay*H2, where Ay is the lateral acceleration of the suspended mass and H2 is the moment arm from the suspension roll center. The second moment is produced at the outboard tires and is (W1+W2)*u*H1, where (W1+W2) is the total trailer weight, u is the road/tire co-effecient of friction, and H1 is the distance from the ground plane to the suspension roll center. A third moment is produced by the suspension itself and is represented by K*h*S, where K is the spring constant, h is the suspension deflection, and S is the suspension track width.

The moments due to the suspended mass and suspension tend to cancel each other since they both act about the suspension roll center. However, on rough roads or when sidewind forces are high, the acceleration of the suspended mass will be great enough to overcome the restoring suspension moment. If the suspended mass moment is of sufficient magnitude, it may initiate a rollover if the co-efficient of friction at the tire/road interface is high. On icy surfaces, where the lateral tire forces are a function of slip, the available restoring moment is a function of the lateral sliding velocity. Therefore, the suspended mass moment can initiate and maintain a trailer in yaw as the tire/road forces decrease with increasing slip.

In summary, there are two main conclusions drawn from the literature. The first is that a blunt trailing edged highway trailer has an aerodynamic mechanism to drive and perpetuate trailer oscillations. This stems from the nature in which vortex shedding along the chord and rear of the trailer acts in phase with the trailer oscillation. The second mechanism is due to the lateral forces created as the trailer rotates about its suspension roll center. Both of these mechanisms extract energy from the wind and forward motion of the trailer respectively in order to maintain trailer oscillation.

# CHAPTER 3: METHODOLOGIES AND MODEL DEVELOPMENT

## 3:1 DATA SOURCES

Evidence in support of the existence of possible dynamic instability is drawn primarily from on-scene investigation of heavy vehicle collisions occurring within Manitoba from December 1985 to May 1986. In all, thirty-two cases were selected for in-depth analysis. Documentation consisted of i)vehicle, roadway, driver, and environmental characteristics, ii) extent of injuries and property damage, iii) collision scene evidence and sequence of events. Photographic evidence was also collected for verification and archival purposes. Cases were selected at random with particular reference to proximity of collision and the probability of arriving on scene before the vehicle(s) were disturbed. A twenty-four hour communications link was established between the University of Manitoba and the Royal Canadian Mounted Police. The focus of the study was to determine the feasability of examining commercial vehicles in their natural environment (on the highway) and thus urban cases were excluded. Weather data was obtained from Environment Canada with particular attention to the magnitude of the variables in question. Further collision data was assembled from discussions with drivers at the scene or in subsequent telephone conversations.

## 3:2 DISCUSSION OF ON-SCENE ACCIDENT INVESTIGATIONS

The accident data analysis is broken down into two sections:

i) examination of individual data elements, and ii) results of Statistical Analysis System (SAS) multivariate analysis.

3:2:1 VEHICLE AND CASE DATA ELEMENTS

Of the thirty two cases selected, the criteria vehicle is involved in 23 single vehicle incidences; 6 cases involve another vehicle, 1 case involves a collision with a road grader, 1 tractor trailer unit struck a pedestrian on the highway, and the final case involves the criteria vehicle colliding with a bridge abutment. This data is graphed in Figure C1.

Twenty of the vehicle configurations are 45 foot single trailers. In two cases, the trailers are 48 foot trailers, where another two tractors are with 21 foot trailers (sand/snow haul). Five configurations are A-train doubles, with one configuration having a B-train double. Two cases concern a tractor which was bobtailing (no trailer). This data is presented in Figure C2.

Excluding the two bobtail cases, 12 of the trailers are vans, five are livestock trailers, and five more are open bulk trailers (hopper bottom). Another five are tanker units, with two more tractors hauling flatdecks. Only one unit is hauling a refrigerator unit (reefer). This data is presented in Figure C3.

A total of 14 trailers were empty with one trailer at a load factor of 25%. One trailer was at a load factor of 75% with the 14 remaining trailers fully loaded. This data is presented in

Figure C4.

Nineteen of the criteria vehicles were travelling at full road speed (60 mph or greater). Twelve vehicles were travelling at speeds between 45 and 60 mph. Only one case happened at a speed less than 45 mph, at an intersection when the criteria vehicle was slowing down for a light. All other cases took place on open highway. This data is displayed in Figure C5.

Fourteen cases took place on a two lane provincial highway with the remaining occurring on the Trans-Canada (four-lane). Of fourteen cases occurring on two lane roads, eleven were on tangents and three were on curves. Of the eighteen cases which took place on the Trans-Canada, thirteen were on tangents and five were on curves. This data is presented in Figure C6.

Eleven cases came about on icy roadways with eight occurring on snow packed surfaces. Nine cases arose on dry roads with four occurring on wet surfaces. One case occurred on a slushy surface. This data is displayed in Figure C7.

### 3:2:2 ENVIRONMENTAL DATA

Thirteen of the cases happened under clear skies with no precipitation. Two cases occurred under light rain and another case under heavy rainshowers. Ten cases occurred under light snow and another involved in heavy snowstorm. This data is displayed in Figure C8.

The average maximum wind value was 11.6 MPH, plus or minus 6.2 MPH. The median (most frequently observed value) was 20 MPH. Fourteen cases had wind values of 20 MPH or greater. Nineteen cases had wind values of 15 MPH or greater. Examining Figure C9, one finds that wind values assume a somewhat normal distribution of about 15 MPH. Although additional wind values would be needed to safely assume that wind speeds are normally distributed about 15 MPH, we can expect 50% of cases to exhibit wind speeds of 15 MPH or greater.

Wind gust was an average of 2.97 MPH with a standard deviation of 3.16 MPH. These figures are somewhat misleading since ten of the thirty-two cases had no observable fluctuation. The median (most frequently observed value) was 5 MPH, with thirteen cases having gust values of 5 MPH or greater. This data is presented in Figure C10.

The wind angle of incidence to the vehicle was an average of 64 degrees with a standard deviation of 47 degrees. The mode (most frequently observed value) was 40 degrees, with observations skewed upwards between angles of 60 to 120 degrees. Fifty percent of observations were between 60 and 120 degrees. This indicates that winds are most likely to be perpendicular to vehicles travelling on Manitoba highways. The majority of Manitoba's provincial roads run in either an East/West or North/South direction. Prevailing winds in Manitoba are from the West to North/West [36]. This data is presented in Figure C11.

Ten cases occurred between twelve midnight and 8:00 a.m., with five cases happening between 5:00 p.m. and twelve midnight. One case occurred around 2:00 p.m., with 16 cases (or 50%) taking place between 10:00 a.m. and 2:00 p.m.. Naturally, the prevailing light conditions coincide with the time of the accident. Thirteen cases occurred in darkness, with another thirteen cases taking place under overcast conditions. One case occurred at dawn under twilight condition with the remaining five cases occurring under clear skies. This data is presented in Figures C12 and C13, respectively.

## 3:3 INTERPRETATION OF AGGRAGATE DATA:RESULTS OF SAS ANALYSIS

Examining individual data elements gives us a preliminary overview of an accident. However, the combination of several or more elements are usually represented in an accident. Often these elements occur together with regular frequency. Both accidents and variables can often be classified into distinct groups. Data from the thirty two cases were analyzed using the University of Manitoba's Statistical Analysis System (SAS) mainframe software.

The SAS program PROC FREQ was used to find groups of variables for pre-collision sequence of events leading up to the collision. PROC FREQ is used normally in finding the frequency of occurrence of one element with respect to another. Pre-collision and collision data was purposely arranged in order of sequence to take advantage of the programs sorting techniques.

PROC VARCLUS is a program which breaks down large pools of data or variables into subgroups [35]. Unlike PROC FREQ, VARCLUS does a multivariate analysis of the total population and combines simultaneously occurring variables into clusters. VARCLUS also does an R squared test to measure the association of variables. This tells the user not only which variables occur together, but also to what degree.

PROC CLUSTER analyzes the similarity of data elements between cases and arranges cases in a hierarchical system based on the total similarity between cases. The resulting "tree" diagram provides the user with information on classes of cases, and also the distance between groups.

In the first run of PROC FREQ, data from the two pre-collision events was used with the main collision event. This was to ensure that PROC FREQ would produce the desired results. It worked with success and a synopsis of all thirty two cases is presented in Table 3.

The next PROC FREQ run was to find the relationship between wind values and the pre-collision sequence of events. This was to assess what effect high winds may have on driver reactions, and also on the outcome of accidents. Wind values were separated into two main groups, those with values less than 15 MPH and those higher than 15 MPH. This was done because the threshold value for wind driven instability of tractor-trailers on icy roads was found to be 15 MPH (see Section 4:1). There were nineteen cases with wind less than 15 MPH, and thirteen cases with wind values over 15 MPH. Nine cases involved empty trailers,

TABLE NO. 1
PRIMARY AND SECONDARY PRE-COLLISION EVENTS WITH MAIN COLLISION EVENT.

| Description | No. of Cases |
|---|---|
| 1) Trailer yaw, skidding, jacknife | 1 |
| 2) Normal straight, run-off-road | 1 |
| 3) Normal straight, "L" collision with other vehicle | 1 |
| 4) Normal straight, rear-end collision with other vehicle | 1 |
| 5) Normal straight, rock cut gave way, rollover | 1 |
| 6) Normal straight, trailer yaw, jacknife | 5 |
| 7) Normal straight, trailer yaw, run-off-road | 2 |
| 8) Normal straight, engine braking, tractor jacknife | 1 |
| 9) Normal straight, rear-pup oscillation, jacknife trailer underride by other vehicle | 1 |
| 10) Normal straight, trailer yaw, evasive maneouver, tire blowout, rollover | 1 |
| 11) Normal straight, full brakes, "L" collision with other vehicle | 1 |
| 12) Normal straight, driver fell asleep, run-off-road | 1 |
| 13) Normal straight, braking on curve, rollover | 1 |
| 14) On curve, trailer yaw, jacknife | 1 |
| 15) On curve, engine braking, run-off-road | 1 |
| 16) On curve, nil, run-off-road | 1 |
| 17) On curve, trailer yaw, hit shoulder, run-off-road | 2 |
| 18) Overtaking, evasive maneouver, hit bridge, rollover | 1 |
| 19) Overtaking, full braking, evasive maneouver, jacknife | 1 |
| 20) Slowing down, tractor yaw, jacknife | 1 |
| 21) Slowing down, skidding, "L" collision with other vehicle | 1 |
| 22) Evasive maneouver, rollover | 1 |
| 23) Full braking, skidding, run-off-road | 2 |
| 24) Full braking, evasive maneouver, jacknife | 2 |
| | TOTAL= 32 |

with eight having loaded trailers occurred on icy roads. Fifteen cases ,irrespective of load were on dry roads. One case with wind less than 15 MPH was a tractor with no trailer. For those cases with winds greater than 15 MPH, 69.2% had empty trailers on icy roads with only 7.7% of cases having loaded trailers on icy roads. Of all thirty-two accidents, eleven cases (34.3%) had loaded trailers on dry roads with winds under 15 MPH. (Figure C14).

Examining Figure C15, we find that trailer yaw and blown-off-road cases account for 61.6% of the pre-collision events for cases with winds greater than 15 MPH. The cases where the trailer hit the shoulder are also wind related, but to a lesser degree than the two previously mentioned categories. Those cases where wind did not play a large or moderate role are classed as "other" and account for 23.1% of cases with winds less than 15 MPH.

Braking on ice account for 36.8% of cases with winds less than 15 MPH, while tractor and trailer yaw account for 10.6% of cases. Once again mechanical, second vehicle driver, and criteria vehicle driver errors are classed as "other" , and these cases account for 52.6% of cases with winds less than 15 MPH.

In Figure C16, the thirteen cases which had winds as either a strong, moderate, or weak factor in the accident are plotted against the critical wind speed for friction values ranging from 0.1 to 0.8 for 45 foot and 48 foot trailers. The cases which had high winds as a dominant factor in the accident are above the critical wind curves, except for one. This single case happened on a wet road under mild winds and the instability was attributed to the combination of winds and the hydroplaning of tires on the wet surface. Hydroplaning of tires can reduce the road friction to values less than that of ice [26]. If we place the single case which occurred on the wet surface (0.5) on the same axis point for ice (0.2), the wind value for this case would be in the critical wind speed range. Therefore, the assumption of hydroplaning for this case is consistent with the theory proposed.

There are three cases in which wind played a moderate role in the accident. The wind values for these cases are situated essentially about the critical wind curve. The two remaining cases in which wind played a minor role are situated well below the critical wind curve. These two cases occurred on dry roads and wind made evasive maneouvers more difficult for the drivers. But, for these two cases wind did not precipitate the accident.

From the data it can be inferred that for tractor-trailer accidents which occur in winds over 15 MPH, wind can either precipitate or aggravate the sequence of events in an accident. In comparison, for cases having winds less than 15 MPH, it can also be inferred that either vehicle malfunction, criteria vehicle driver or second vehicle driver error is the dominant feature in these accidents.

Wolkowicz and Billing [2] conducted an on-scene commercial vehicle accident survey in the Province of Ontario during the winter of 1981, and collected data on 151 accidents involving heavy trucks. This survey was used as a model for the University of Manitoba study.

Data for jacknife and rollover accidents are plotted in Figures C17 and C18, respectively. In both figures, the trailer loading and road condition is noted. We find that for Wolkowicz and Billings' data, 74.2% of jacknife accidents happened on icy or wet roads with empty trailers, whereas full trailers on wet or icy roads accounted for only 15.2% of jacknife accidents.

In Figure C18, we find that loaded trailers on dry roads accounted for 70.6% of rollover cases. Loaded trailers on wet roads accounted for only 17.6% of rollover accidents.

Wolkowicz and Billing attribut these observations to the fact that loss of traction is much greater with empty trailers on an icy surface. For loaded trailers on dry roads, they contend that the centrifugal force of a payload is able to overcome the payload weight. The lateral friction at the tire/road interface provides sufficient lateral acceleration to cause the trailer to rotate about its outboard tires.

However, in Wolkowicz and Billings' study, the authors concluded that the driver was responsible for 88% of all accidents. The main causal factor cited was travelling too fast for prevailing conditions. In only 5 of 151 cases studied by Wolkowicz and Billing is wind alluded to as a factor. Yet, in their section describing on-scene investigation methods, they state that the frequency of commercial vehicle accidents is weather related [36]. The question raised is how is a driver to know what is a safe speed for the prevailing conditions?

Driver interviews are not indicated in the data gathering mechanisms of the Wolkowicz and Billings' study, and it is assumed that they chose to gather as much information as possible without becoming too involved in individual cases. For the Manitoba study, driver interviews were conducted when possible to gather information on driver actions and descriptions of vehicle behaviour during the accident.

This proved to be both a positive and negative feature of the study, since some drivers were reluctant to divulge information fearing reprisals from employers or the police if the author leaked information. Other drivers were more than willing to talk about their accident. Some simply wanted an audience to hear their saga, while others wanted to displace as much blame as possible on external factors. It was these interviews which pointed to wind as a causal factor in heavy truck accidents.

One of the problems with on-scene accident investigations, and the University of Manitoba Study is no exception, is that the collision resume is an evaluation of the incident based in part on the investigator's judgement. Data from the Manitoba study was analyzed using SAS VARCLUS to verify the investigators assessment of accidents. There are two options in the SAS VARCLUS program. The first is that the user is allowed to specify which variables will be tested by using the SEED option. The second allows the computer to randomly cluster variables based on the algorithm supplied. The R squared test is used to measure the affinity of variables. An R squared value of one means that the dependent variable has a strong correlation with the independent variable. An R squared value of zero means that the dependent variable has no correlation with the dependent variable. The author chose the RANDOM option with ouput noted in Figure C19.

Examining Figure C19, we find that for the first cluster the following variables were grouped:

1) Precipitation (PREC)
2) Maximum wind value, includes gust (MAXWIND)
3) Road surface environmental condition (RSURENV)
4) Pre-collision sequence of events no.1 (PCS1)
5) Pre-collision factors no. 1,2,and 3. (PCF1,PCF2,PCF3)
6) Vehicle speed (VSPEED)

Precipitation, wind, and the road surface environmental condition show a strong affinity for each other. Looking at the weather data we find that high winds accompany precipitation in 80% of cases. Naturally, icy, snow packed, or wet roads are a direct result of the amount and type of precipitation.

The first pre-collision event is shown to have a moderate association with wind and road surface condition. Since trailer and tractor yaw and braking on ice occur in 60% or more of cases, the program was able to group this variable together with wind and icy roads.

Since icy roads, winds, and braking occur in nine of thirty-two cases and are coded as pre-collision factors, the program grouped these variables with the previously mentioned group. The degree of association is shown to have a mild to moderate affinity with the others.

For cases which had icy roads as a factor, some drivers reduced their vehicle speed to maintain safety. This action was made regardless of wind speed. Therefore, VSPEED is grouped within the cluster which contained RSURENV and shows a mild association with other members in the cluster.

Cluster number two contained the following variables:

1) Number of trailers (NUMTRAIL)
2) Number of trailer axles (NUMTAX)
3) Converter type (CON)
3) Trailer type (TRTYPE)
4) Length of trailer number two (TR2LEN)

Of course the number of axles in a configuration is directly related to the number of trailers a tractor is carrying. Single trailers always have single axle or tandems. (In Manitoba tridems are now allowed.) The number of trailer axles has the strongest R squared value of all variables at 0.934. However, this is somewhat distorted since the majority of cases had 45 foot tandems as the trailer. Variables CON, TRTYPE, and TR2LEN are grouped in descending order. This is most probably due to the low number of double trailer units, coupled with the high number of van units. The algorithm must have assumed that the codes for these variables occur together. But in fact, the trailer type has little, if anything, to do with the configguration. Rather, it is load dependent. It is a given that a converter is needed to connect the two trailers together.

There is one surprise grouping. The algorithm clusters LOAD with LIGHTCON and TR1LEN. The grouping of LOAD with TR1LEN is not a surprise due to the fact that lightly loaded van trailers account for a good proportion of cases. But, the grouping of LIGHTCON with these does seem odd. Going back to each individual case, we find that the majority of accidents with loaded trailers occurred between 5:00 a.m. and 8:00 a.m.. Motor carriers, as with most transportation firms, collect freight from customers during the day. Highway trailers are then loaded and dispatched for arrival the next morning. Therefore, most tractor-trailer units on the road after 5:00 p.m. can be assumed to be fully loaded.

The second observation is that most accidents which involve lightly loaded trailers occurred during daylight hours and belonged to rural cartage companies or private firms. These firms often come into a major city to pick up a load, but have insufficient freight to load a trailer for the trip in. This is called "deadheading". Large motor carriers which operate between major urban centers move empty trailers only if absolutely necessary. Therefore, the program is able to identify this aspect of operations by clustering accident variables.

Remaining variables were grouped according to the following:

Cluster 7- 1) Wind angle (ANGLE)
2) Road alignment (RALIG)
Cluster 6- 1) Collision sequence of events no. 1 & 3. (CSE1,CSE3)
Cluster 4- 1) Pre-collision sequence of events no. 2 & 3 (PCS2,PCS3)
Cluster 3- 1) Collision type (COLTYPE)
2) Collision sequence of events no. 2 (CSE2)

Since wind angle was normally between 60 and 120 degrees, and road alignment was straight, the algorithm grouped these two variables together showing a mild association with each other. For CSE1 the majority of cases are jacknife, trailer yaw or run-off-road, while CSE3 is coded "0" meaning that there is no third collision event. Therefore, the algorithm group these two variables with a moderate association.

COLTYPE is coded mostly with "0", meaning it was a single vehicle accident, while variables CSE3, PCS2, PCS3 are coded with "0", meaning that there is no second or third event. Therefore, the algorithm has no choice but to group these variables together accordingly.

The conclusion drawn from this analysis is that combinations of particular environmental, vehicle and driver factors can be identified with specific types of accidents. Although coded records such as the accident cases in this study can be used in VARCLUS, the program would be better suited for measured data. For example, if one had traffic counts, frequency of particular types of accidents, and the population of truck configurations travelling on particular highways, VARCLUS could group this data very well.

In the second method, accidents are classified by type through the use of SAS CLUSTER. This program groups records according to the similarity between identical variables across records. The program starts by grouping each individual record as a cluster and progressively lumps similar records together until one large cluster (the database) is formed. There are various clustering algorithms available. The author chose McQuittys' similarity analysis since it is less sensitive to outliers than other programs [33,34]. The output is shown in Figure C20.

Examining Figure C20, we find that three main groups, or classes of accidents emerge from the data. Group 3 has the most similarity among its cases. The main features of these accidents are:

1) Trailer yaw is the pre-collision event.
2) Empty or partially loaded trailers.
3) Icy roads.
4) High lateral winds.
5) High gust.
6) The prevailing wind angle is between 60 and 120 degrees to the trailers.
7) All have precipitation accompanying the high wind (usually snow).
8) Nine have 45 foot vans; one is an open bulk double configuration.
9) All except two occurred during daylight hours.
10) All except one are single vehicle accidents.

The second group has cases with more dissimilarities among them than Group 3, but most have the following similarities:

1) Braking or evasive maneouver as driver actions.
2) Icy or wet roads.
3) Partially or fully loaded trailers.
4) Mild to moderate winds, no gust.
5) Most are single vehicle cases.

The first group has the following attributes:

1) Mild to no winds.
2) Dry roads.
3) Partially to fully loaded trailers.
4) Tractor-trailer was involved in collision with second vehicle in which second driver was also a factor or at fault.

The main conclusion drawn from this analysis is that wind driven instability of tractor-trailer rigs can account for a much larger proportion of accidents involving these vehicles than was previously suspected. As stated earlier many of these accidents are masked by simply coding the incident as "driver loss of control". Rather, it should be stated that the driver failed to regain control of a vehicle that was rendered unstable by an external source, namely wind.

In the second group of accidents, moderate winds and braking are cited as commonly occurring elements. A vehicle travelling on slick roads still has sufficient lateral tire/road friction to overcome the action of moderate sidewinds. However, this changes when the driver locks the brakes. Sidewinds now have sufficient force to affect vehicle stability due to the sudden loss of lateral tire/road friction. Therefore, in these cases wind may not initiate trailer yaw, but it aggravates the situation.

## 3:4 MODELLING ENVIRONMENTAL AND MECHANICAL PARAMETERS

### 3:4:1 SUSPENSION CONSIDERATIONS

In the early stages of development, suspension effects were excluded in order to maintain simplicity. It was later determined that a trailer body oscillating about its suspension roll center can provide one of the mechanisms to sustain motion (Figure A5). If the lateral force produced by suspension roll is greater than the friction force available at the tire/road interface, "break-away" will result. This will either initiate the trailer into yaw or stabilize it depending on direction of roll and trailer yaw angle.

### 3:4:2 TRUCK TIRES AND ROAD/TIRE CO-EFFECIENTS OF FRICTION

Heavy truck tires are markedly different from passenger car tires in both material and carcass construction and thus possess dynamic performance characteristics which are distinct unto themselves. Commercial vehicle tires have load requirements 10 times that of passenger vehicle tires and experience inflation pressures of 3 to 4 times that of passenger car tires [26]. Truck tires utilize rubber compounds which provide long wear capabilities but sacrifice road/tire tractive friction. In some cases, truck tires possess co-efficients of friction which are 40-60% that of comparable passenger car tires under similar conditions [27]. Thus, truck tires develop lower lateral tire/road forces which render commercial vehicles less stable than passenger vehicles.

The second major difference is the carcass construction. As mentioned, truck tires have a higher load bearing requirement than auto tires [28]. Commercial vehicle tires have both stronger and a greater number of wound cords in the carcass rendering them more rigid and as a result do not develop comparable sideslip as their passenger car cousins. Consequently, commercial vehicles are more prone to develop vehicle yaw due to a loss of lateral flexibility.

Road/tire friction values are dependent upon the surface the tire is in contact with and, as a result, the available braking force is proportional to the friction value regardless of tire slip [25,26,28,33]. Tire slip is defined as the ratio of tire velocity divided by vehicle velocity. However, lateral forces are dependent on wheel slip since the maximum forces are experienced in the longitudinal plane of the vehicle. Lateral forces are thus proportional to wheel slip. Anyone locking their car tires on an icy road while attempting to turn a corner experiences the panic of nil response to steering input. Once they let their foot off the brakes and maximum lateral forces are developed, the vehicle responds accordingly. (Figures A6 and A7).

Road surface contaminants also play a large part in friction force reduction between tire and roadway. Loose gravel for instance can have friction values below that of hard-packed snow. Small gravel particles act as microscopic ball bearings which the tire rides on, thus reducing the adhesion between the rubber tire and contact surface [33]. The same phenomenon occurs between a tire and hard-packed snow or icy surface. Under extreme cold temperatures, ice develops friction values similar to asphalt [26]. But due to contact pressure from the weight of the vehicle, a film of water develops between the tire and ice which acts as a lubricant. This is why a vehicle spinning its tires on ice often requires an external push to induce motion.

The roadway co-efficients of friction were measured at on-scene accident investigations using a ten pound dumbell placed in a quarter section of tire attached to a spring scale. The force needed to sustain motion was divided by the weight to estimate the friction value. Despite the crudeness of the instrument, values came well within the ranges indicated in Table 2, which where derived using full scale vehicle tests.

TABLE 2: TYPICAL VALUES FOR TRUCK TIRES UNDER VARIOUS CONDITIONS

| Surface type | Friction value |
|---|---|
| 1) dry pavement | .65-.85 |
| 2) wet asphalt | .45-.70 |
| 3) loose snow (on asphalt) | .33-.55 |
| 4) packed snow (on asphalt) | .15-.35 |
| 5) ice on asphalt ** | .08-.25 |
| 6) lubricated ice (on aphalt) ** | .03-.15 |

NOTE: ** Also depends on surface texture.
(Sources: Reference No. 26,27,28,34)

A highway tractor is comparable to a trailer in weight, yet does not possess the surface area to develop sidewind forces that a trailer experiences. Thus a tractor acts as a moving "anchor" point for the trailer oscillating about the vertical axis of the tractor's fifth wheel. The moments outlined in Figure A4 summate about the kingpin and produce the yaw described in following sections. Since it is difficult to measure the co-efficient of drag and lift for such a body subjected to a varying airstream, the wind forces will be simply pressure by the effective surface area. Therefore the describing equation, in its simplest form is:

$$I_{zz}\ddot{\theta}=\sum_{i=1}^{5} M \qquad (1)$$

where $I_{zz}$= Trailer moment of inertia about the kingpin.
$\ddot{\theta}$= Lateral yaw acceleration of trailer.
$\sum_{i=1}^{5} M$= Summation of moments M1 to M5 about the kingpin.

To expand the driving moment M, the physical and mathematical relationships causing moments M1 to M5 must be stated explicitly. Moments M1 & M2 are produced by wind pressure acting against the effective side area of the trailer. Taking an infinitesmal strip along the longnitudinal axis of the trailer, the moment arm is the distance from the kingpin to the strip. Thus the wind pressure and moment arms for the frontal and side wind forces are a function of the yaw angle. Integrating along the longitudinal axis gives the total moments produced by the frontal and side winds (Figure A4 & A5).

$$M1 = \frac{1}{2} \rho C_D A V_F^2 \sin^2\theta \, L_1 \qquad (2)$$

$$M2 = \frac{1}{2} \rho C_D A V_W^2 \cos^2\theta \, L_1 \qquad (3)$$

$L_1$ = moment arm from center of area to kingpin
$\rho$ = air density.
$A$ = effective area of trailer
$\cos\theta, \sin\theta$ = cosine and sine of yaw angle theta.
$V_F$ = vehicle velocity (frontal wind velocity).
$V_W$ = crosswind velocity.
$C_D$ = co-efficient of drag.

From this simple analysis one can easily reason that the destabilizing moment due to crosswinds is a squared function of the wind velocity. For example, if wind velocity increased from 20 mph to 25 mph (25% increase) the moment would increase by 56 per cent.

$$M3 = \mu N L_2 \left| 1 - \frac{L_2 \dot{\theta}}{V_F} \right| \cos\theta \qquad (4)$$

$\mu$ = co-effecient of tire/road friction
$N$ = weight of trailer (lb.-force) at rear tandems
$L_2$ = distance from center of force to kingpin
$\cos\theta$ = cosine of yaw angle theta
$\dot{\theta}$ = yaw velocity (radians/unit time)
$V_F$ = vehicle velocity (ft./sec.)

M3 is the moment due to tire/roadway friction taken about the kingpin. This moment is affected not only by the co-efficient of friction, but the lateral velocity of the trailer as well. Figure A7 demonstrates the effect of lateral friction availability as slip increases. As the yaw velocity increases, the ratio of forward to lateral velocity decreases, and if sufficient enough, wheel-lock will result.

$$M4 = K L_2 \frac{S^2}{h_2} \sin \sqrt{\frac{K}{M}\frac{S^2}{h_2^2}}\,(t) \qquad (5)$$

$K$ = suspension spring constant (lb.-force)
$S$ = distance from suspension roll center to spring center (ft.)
$h_2$ = distance from suspension roll center to center of suspended mass (ft.)
$L_2$ = distance from center of suspension force to kingpin. (same as for M3)
$M$ = sprung mass of trailer

M4 is the moment due to the trailer box oscillating about the suspension roll center. The lateral force produced by the sprung mass of the trailer box is counteracted by the suspension. Yet a substantial lateral moment is still produced which can have a significant effect on lateral stability.

$$M5 = \frac{1}{2} \rho C_D A_2 V_F^2 \sin / .3 \frac{V_F}{D} / (t) L_3 \qquad (6)$$

$\rho$ = air density
$V_F$ = frontal wind velocity (as per M1)
$A_2$ = area of latter third of trailer
$L_3$ = distance from latter one third of trailer to kingpin
$t$ = time (sec.)

M5 is the moment produced by vortex (wake) shedding from the rear of the trailer. The effect of the vortices on the windward side of the trailer are reduced due to the crosswind. However, when the trailer swings into position to the maximum on the windward side, the moment is increased due to additive effects of both the cross and frontal winds.

Combining the five equations describing the major lateral moments results in a second order, non-linear differential equation as follows:

$$I_{zz}\ddot{\theta} = \frac{1}{2}\rho C_D A L_1 \left[ V_W^2 \cos^2\theta \pm V_F^2 \sin^2\theta \right] + L_2 \left[ {}_1\mu N \sin\theta \left| 1 - L_2 \frac{\dot{\theta}}{V_F} \right| \pm K \frac{h_1^2}{h_2} \sin \sqrt{\frac{K}{M}\frac{h_1^2}{h_2^2}}\,(t) \right] + \frac{1}{2}\rho C_D L_3 A_2 V_F^2 \sin \left| .3 \frac{V_F}{D} \right| (t) \tag{7}$$

The equation requires numerical methods in order to derive the yaw as a function of time.

Parameters were changed in a PC based LOTUS spreadsheet to determine the effects of the individual parameter variations.

The resultant non-linear second order differential equation describing trailer yaw as a function of time was integrated by using fourth-order Runge-Kutta methods [5] in a LOTUS 1-2-3 spreadsheet to take advantage of both the calculating speed and graphic capabilities of LOTUS. Output was saved and displayed using either LOTUS or CHART-MASTER depending on the limitations of each package. The spreadsheet layout is presented in figure C21. The use of Runge-Kutta techniques requires small integration step-sizes, which necessitated the use of 286 based PC with expanded memory board (790K).

The optimum would be a 386 based machine with expanded memory to take advantage of smaller stepsizes for accuracy and speed of calculation. Each simulation run took approximately 2 minutes to calculate and display the results.

# CHAPTER 4: DISCUSSION OF RESULTS

There were two sets of simulation runs performed to determine the effects of parameters; one for environmental factors and the second for mechanical factors. For environmental factors a road friction value of 0.35(loose snow) was used since this was the most commonly occurring value in actual accident cases, with vehicle speed set at 60 mph and cargo equal to 0. In essence, the simulation was of an empty tractor-trailer travelling at highway speed on snow-covered roadways subject to varying wind conditions.

In the second simulation, vehicle parameters were changed under a standard set of environmental conditions. Wind was set at 20 mph (no gust) perpendicular to the trailer with a road friction value of 0.35. Once again this was to simulate a tractor-trailer travelling on a snow-packed highway subject to varying human controllable vehicle factors.

The results were predictable based on each parameters influence in Equation 7, with one exception. In 20% of cases the yaw angle diverged with no upper bounds. In real life this would be analogous to the trailer spinning about its kingpin like a propeller! After examining the aerodynamic moments it was found that both wind gust and vortex shedding play dual roles in both yaw excitation and damping, thus verifying the works of the authors in References 20,21,22,29,30, and 31 which will be discussed in subsequent sections.

In all cases the results predict increased instability for 48 foot trailers in comparison to 45 foot trailers. A 48 foot trailer has 7% more side area and 10.5% more moment arm than a 45 foot trailer. Since both frontal, vortex, and side wind moments are a product of the effective area and moment arm, the 48 foot trailer experiences an increase of 18.23% in the influence of aerodynamic parameters over a 45 foot trailer.

## 4:1 INFLUENCE OF ENVIRONMENTAL FACTORS

### 4:1:1 EFFECT OF WIND SPEED

In Figure B1, the average absolute maximum yaw angle is plotted against increasing wind velocity for the base case for both 45 and 48 foot trailers. As predicted, the yaw angle increases as a squared function of the wind velocity. However, as the magnitude of wind velocity approaches the value of frontal wind velocity (i.e. vehicle speed of 60 mph) it reaches a maximum of 18 degrees for a 45 ft. trailer, and 21 to 24 degrees for a 48 ft. trailer, respectively. It is at this point that the frontal wind moment produced by the moving vehicle counterbalances the side wind moment.

Rather than braking to attempt to regain control of a yawing trailer, a driver should use the influence of frontal wind and tire lateral forces to regain control by accelerating. Although this sounds illogical, accelerating causes an increase in the frontal wind moment which forces the trailer back into a stable state.

In both cases the most significant increase in yaw angle is between 10 to 30 mph. In this regime the side wind moment is still significantly below that of the frontal wind moment. The main conclusion from this observation is that while it takes a large wind to reach the maximum theoretical yaw angle, it only takes a small wind (10 to 15 mph) to initiate a tractor-trailer into yaw on icy roads. The second observation is that for lower wind values, there is essentially no difference in stability between 45 and 48 foot trailers. This is attributed to the absence of wind influence.

<u>4:1:2 EFFECT OF WIND GUST</u>

It is interesting to note that for Figure B2, the upper wind limits of 45 mph produce almost 15 additional degrees of yaw over the upper wind limits of 60 mph in Figure B1 for both 45 and 48 foot trailers, indicating that wind gust has a major influence on vehicle stability.

In Figure B2, the gust range varied from 0 to 30 mph with a base wind of 15 mph, which resulted in a yaw angle range of 5 and 8 degrees at 0 gust, to 18 and 28 degrees at a gust of 30 mph for 45 and 48 foot trailers, respectively. As per Figure B1 the most significant increase in yaw is observed between 0 and 20 mph with a maximum reached at a gust range of 30 mph. As in Figure B1, the side wind moment is a squared function of wind velocity with the side wind moment being counterbalanced by frontal wind moments at the high ranges.

Approaching the above observations from a theoretical point of view, highly variable winds provide a fluctuating pressure force on the body of a trailer. From Newton's laws, a body will remain at rest until acted upon by an external unbalanced force. Once motion has been established, inertia forces assist in sustaining yaw. In Figure B3, both yaw angle and wind gust are plotted against time. At T=8 seconds, a major gust initiates the trailer into yaw, but at T= 11 to 15 seconds, a drop in gust increases stability. At T=20 seconds, another major gust once again initiates the trailer into yaw. However, at T= 20,28,32,42,44,51 and 57 seconds the motion of the trailer is in phase with the wind gust. At T= 30,34,45,53 and 58 seconds, a sudden drop in the gust value results in the side wind moment being dampened by the frontal wind moments.

Moncary, Barlow, and Hawks [29], conducted similar simulations of wind gusts using much more sophisticated computer models and concluded that wind variance (i.e. wind gust) provides one of the major excitation mechanisms in articulated vehicle instablity. Therefore, a tractor-trailer under the influence of a high but constant wind can essentially be considered static, while a smaller but variable wind is dynamic and thus has a greater effect on vehicle stability.

4:1:3 EFFECT OF WIND ANGLE

In Figure B4, the wind angle is varied from 0 (vehicle travelling into a headwind) to 80 degrees (wind perpendicular to trailer) with yaw plotted as the dependent variable. The results show that for both trailer lengths, a minimum is reached at approximately 45 degrees. At 0 degrees, the additive effect of the vehicle speed (60 mph) plus wind velocity of 20 mph results in an effective wind speed of 80 mph. Since aerodynamic moments are a squared function of wind velocity, this results in a 78% increase in the effect of frontal wind moments. Despite a minimum yaw angle, the frontal winds can exert a sufficient force if the vehicle is travelling into a wind. In the range of 30 to 45 degrees, the additive effects of the side wind vector plus frontal wind vectors are reduced with the influence of the lateral wind vector not yet fully developed. As the wind angle increases to a perpendicular position, the additive effect of frontal wind is reduced with the influence of the side wind reaching a maximum. The yaw angles recorded are higher those recorded for other simulation runs, due to the additive effects.

The conclusion drawn here is that when a wind is perpendicular to the vehicle, the side wind moment is dampened by the frontal wind moments. But if a wind is at an angle to the trailer, the X and Y vector components of wind tend to cancel each other, with the two vectors being equal at 45 degrees. However, if a wind is approaching a trailer from 90 to 180 degrees, the two vector components assist each other in driving the trailer into instability.

<u>4:1:4 EFFECT OF ROAD/TIRE FRICTION</u>

In Figure B5, yaw angle is plotted against increasing road/tire friction values. As expected, yaw angle is inversely proportional to the co-efficient of friction. Yaw varies from 17 and 4 degrees for a co-efficient of 0.2 (glare ice), to 24 and 8.5 degrees for a co-efficient of 0.8 (dry asphalt), for 45 and 48 foot trailers, respectively. The largest decrease is between 0.4 and 0.8 due to higher available friction values. As indicated in Appendix A, road friction is decreased proportionally with the lateral velocity to simulate wheel slip and hence the vehicle travelling on a lubricated surface. This is eliminated at friction values of 0.4 and up to simulate a non-lubricated surface with the expected result of a more rapid drop in yaw for friction values of 0.4 and over. Modern truck and car tires have tread designs which prevent hydroplaning (riding of the tire on a film of water during rainshowers) and thus maintain good contact with the road. However, this does not hold true on icy highways unless the tire is studded. Therefore the problem of loss of lateral stability still remains on snow or ice.

In Figure B6, an empty 45 foot trailer under the influence of a 20 mph wind (no gust) is simulated with friction values of 0.2 (glare ice) and 0.8 (dry asphalt) with yaw plotted on the same graph. The maximum yaw for a friction value of 0.2 is 38 degrees and only 10 degrees for a friction value of 0.8. Also, the yaw frequency for friction value of 0.2 is 0.27 HZ and 1.16 HZ for a friction value of 0.8, clearly demonstrating the influence that road/tire friction has on vehicle stability. The smaller yaw angles at high yaw frequencies for large friction values indicate that lateral road/tire friction has an immediate self-correcting effect on trailer yaw which is absent at lower friction values.

Chinn and Neilson [34] conducted full scale locked wheel tests on various road surfaces to determine the influence of friction values and vehicle speeds on trailer yaw. For an unloaded vehicle travelling at 40 Km/hr, the maximum yaw recorded is 32 degrees for a friction value of 0.2 and 7 degrees for a friction value of 0.8 degrees. The results for locked wheel tests indicate that for a free rolling tire on a dry, clean asphalt the same lateral forces can be expected while a tire on a low friction surface loses lateral force due to wheel slip, corroberating the author's findings.

One of the most common statements made during driver interviews was that the trailer had developed yaw before the driver had noticed his vehicle was approaching instability. Most drivers locked the trailer brakes under the notion that "the road would pull the trailer straight". In Figure B7, the same empty 45 foot trailer on an icy surface (0.2) with a 20 mph wind (no gust) is simulated with the brakes locked at T=40 to 60 seconds. With a fully locked wheel, lateral forces are reduced to a minimum. As indicated in Figure B7, not only does the yaw frequency increase, the yaw angle increase to 44 degrees, aggravating the situation. The correct procedure would be to leave the trailer alone, or increase speed momentarily to take advantage of frontal wind damping. Although this may appear to be a contradictory statement, the same logic is expressed by Telionis et al [31] who conducted tow tank tests on passenger cars passing articulated vehicles.

## 4:2 INFLUENCE OF VEHICLE/OPERATIONAL FACTORS

### 4:2:1 EFFECT OF VEHICLE SPEED ON FRONTAL AND VORTEX SHEDDING MOMENTS

One of the major influencing factors in vehicle stability which has long been known to the general population is the speed at which you travel. This is more the case when articulated vehicles are concerned since they are not one unit as in a passenger car, and the oscillation of the trailer about the kingpin is not felt by the driver until yaw is present. Therefore, a passenger car driver has the ability to respond to adverse wind conditions prior to the vehicle developing potentially uncontrollable yaw whereas a truck driver may never have the opportunity to feel the force until after severe yaw develops.

In Figures B8 to B12, a 45 and 48 foot empty trailer is simulated on a road friction surface of 0.35 (loose snow) with a 20 mph side wind (no gust) travelling at speeds between 20 and

60 mph.

In Figure B8, yaw ranges from 4.7 and 5.8 degrees at a road speed of 20 mph to 13.2 and 14.9 degrees at a road speed of 60 MPH for 45 and 48 foot trailers, respectively. A side wind is used to initiate the trailer into yaw to ascertain the effect of corresponding frontal and vortex aerodynamic moments at various vehicle speeds. In Figures B8 and B9, the magnitudes of both the frontal and vortex shedding moments increase as a squared function of the vehicle speed which results in a corresponding increase in yaw as well. However as the vehicle begins to approach 60 mph there is a decrease in the yaw gradient which begins to reach a maximum at 60 mph. Unlike the side winds which are dampened by the frontal winds, frontal winds develop self-damping effects at higher vehicle speeds. Referring to Figure A2, side winds force a trailer into positive yaw (direction of wind) which is forced back by the frontal winds (dampened). As the trailer swings about the longitudinal axis into negative yaw (against the side wind) the frontal wind now acts to assist the side wind and excite the trailer back to a positive yaw position.

At lower vehicle speeds frontal and side wind moments are insignificant in comparison to inertial moments, and as a result a quasi-steady state oscillation of the trailer about the kingpin is produced. However, at higher vehicle speeds, the influence of the frontal moments surpass both the side wind and inertial moments, which results in self-damping as the trailer oscillates about the kingpin [29,30,34]. This is the logic mentioned in the previous section as to why a driver should increase speed in order to correct a trailer in yaw.

There is one scenario which leads to instability regardless of vehicle speed, and is in fact exacerbated by increased velocity. This is when the frontal wind moment and yaw frequency synchronize with the vortex shedding moment produced at the rear of the trailer causing the trailer to diverge in yaw. In Figure B10, the yaw frequencies (HZ) for 45 and 48 foot trailers along with the Karman vortex shedding frequencies [6-23] are plotted against vehicle speeds of 20,40, and 60 mph. The yaw frequencies for 45 and 48 foot trailers increases proportionally with the shedding frequency. Also, it is observed that the yaw frequencies are a multiple of the vortex frequencies. A linear regression was conducted on the observations with the following results shown in Table 3.

TABLE 3: X AND Y LINEAR REGRESSION VALUES FOR 45 AND 48 FOOT TRAILERS.

| Trailer Type | X Co-efficient | Y-Intercept |
|---|---|---|
| 45 Ft. | .660 | .160 |
| 48 Ft. | .687 | .310 |

In both cases the standard error of 0.01 was a good fit for the limited number of observations. Combining the X and Y regression values, it was determined that the frequency difference between 45 and 48 foot trailers and the vortex shedding was 45 and 60 degrees, respectively. These results are somewhat misleading since the number of cycles of yaw was averaged over the simulation period for non-divergent cases. Trailer yaw frequencies were sporadic during simulations (as would be the real world case) and thus no single pattern emerged as the dominant case. What the data does indicate is vortex shedding has an increasing influence on trailer yaw as the shedding frequency and strength increases with vehicle speed.

In Figure B11 and B12 frontal and vortex shedding moments are plotted against time for both divergent and steady-state trailer oscillation. In Figure B11, between T=15 to 30 seconds, trailer yaw and thus the frontal wind moment begin to lock in phase with the vortex shedding frequency. However, as the trailer swings beyond 10 degrees, the vortex excitation is lost and the trailer does not develop self sustaining motion in phase with vortex shedding. At the peak in frontal wind moment, between T=21 to 23 seconds, two vortices assist the frontal winds to increase yaw, but an additional vortex at T=24 seconds, 180 degrees out of phase with yaw, immediately subdues oscillation. The cycle once again repeats at T=38 to 50 seconds with the same results, demonstrating the cancellation effect of wind moments which are 180 degrees out of phase with each other.

In Figure B12, the reverse case of the above is true. When wind moments are locked in phase, the effect is to asymptotically increase trailer yaw to the point of instability. At T=20 seconds, a vortex is both in phase and at maximum amplitude with trailer yaw and thus the frontal wind moment. At T=20 to 42 seconds trailer yaw tends to coincide with vortex shedding, but phase lock is not yet fully established. At T=42 to 60 seconds, trailer motion is now fully locked in phase with vortex shedding and continues to increase asymptotically as the vortices provide the mechanism to sustain oscillation. As trailer yaw continues to increase with each cycle, the frontal wind moment also increases in influence, and diminishes the effect of lateral road/tire and side wind moments. Although the works of Shiraishi and Matsumoto [22], Komatsu and Kobayashi [21], Wood [20], and Olivari [23] deal with various shaped prismatic bodies under numerous wind conditions, the conclusions are essentially the same. Vortex shedding provides a mechanism to extract energy from a wind stream to drive a mechanical system in oscillation. This fact also holds true for large commercial vehicles subject to fluctuating wind conditions.

4:2:2 EFFECT OF CARGO WEIGHT

Increasing cargo weight affects the mechanical characteristics of the trailer in three ways. It i) increases the mass moment of inertia, ii) increases the normal force for lateral friction forces, and iii) decreases oscillation frequency of the sprung mass about the sprung mass center.

In Figures B13 and B14, yaw angle and frequency (HZ) is plotted against increasing cargo weight (lb). As expected yaw angle is inversely proportional to increasing cargo weight while yaw frequency is proportional to cargo weight. What is unexpected is the similarity in values for both yaw angle and frequency at high cargo ranges for both 45 and 48 foot trailers. Also, the yaw angle gradient for 48 foot trailers is more rapid than for 45 foot trailers, while for yaw frequency gradients, both trailers are essentially the same.

At lower cargo values, the aerodynamic moments have a greater effect on longer trailers due to the increased surface area in comparison to a shorter trailer, and therefore mechanical characteristics play a lesser role in vehicle stability. However, when increasing cargo weight (a mechanical paramater) surpasses the influence of aerodynamic moments, vehicle stability becomes a function of the mechanical characteristics of the trailer itself. Since the mass moment of inertia is proportional to the sum of trailer and cargo mass, a larger wind force is required at higher cargo loadings to overcome inertia and maintain a trailer in yaw.

In Figure B13, for cargo weights of 20,000 lb. and under, the difference in yaw angle is approximately 12%, which corresponds to the difference in aerodynamic moments between 45 and 48 foot trailers. However, at cargo weights of 30,000 lb. and over, the difference in yaw angle between 45 and 48 foot trailers is only 4.1% which corresponds to the 6.2% difference in trailer length between 45 and 48 foot trailers. In Figure B14, for lower cargo values, the difference is once again approximately 16%, which coincides with the difference in aerodynamic moments between

45 and 48 foot trailers, whereas at higher cargo values, yaw frequencies are essentially the same.

The conclusion drawn from this analysis is that for longer tractor-trailer combinations, aerodynamic effects insofar as cargo loading is concerned, play a major role in vehicle stability. For lightly loaded trailers, the difference in yaw angle and frequency between various trailer lengths is a function of aerodynamics, whereas for fully loaded trailers, the difference is based solely on trailer characteristics. The trend towards longer tractor-trailer combinations, coupled with the employment of lightweight engineering materials in body construction to reduce tare weight, will result in an exacerbation of negative aerodynamic effects.

### 4:2:3 EFFECT OF SUSPENSION

While the focus of this work has been primarily on aerodynamics of trailers, certain mechanical parameters which interact with environmental factors have a distinct impact on vehicle stability. Suspension action provides a means of extracting energy from the forward motion of the vehicle and road undulations, which result in yawing action of the suspended mass about the suspension roll center. Moncarz, Barlow, and Hawks [29] determined in their computer simulations that the height of the sprung mass has an appreciable influence on vehicle stability. However, since the height of sprung mass is uniform (6.5 ft.) for most commercial trailers, this parameter was not varied in the current analysis. The load carrying capacity of most commercial leaf springs is approximately 9,000 lb.[35], which corresponds to a maximum load carrying capacity of 36,000 lb. for a set of trailer tandem axles, which is the allowable limit in most jurisdictions. This results in a maximum available lateral thrust of 4,100 lbs at a spring deflection of 18 inches. A simple sinusoidally varying spring action is used in order to maintain simplicity and separate the influence of suspension and aerodynamic moments.

In Figure B15, the yaw angle is plotted against the spring force. It was found that yaw angle is inversely proportional to spring force, despite the spring force being a proportional variable in Equation (7). This would relate to a correcting effect that stiffer springs would have on trailer yaw about the kingpin. Stiffer springs do not allow for lateral acceleration of the sprung mass about the suspension roll center, and as a result opposing forces due to spring action is felt more quickly. Therefore, although yawing action of the sprung mass about the suspension roll center is decreased, the yaw frequencies of stiffer springs allows for self-correction of lateral forces due to the sprung mass about the trailer kingpin.

Although the influence of suspension action about the trailer kingpin is minimal in comparision to aerodyamic and lateral road/tire forces, suspension action provides one of the mechanical means of sustaining motion. The influence of suspension therefore remains constant at all environmental and cargo loading values.

CONCLUSIONS:

i) SAS multivariatate analysis of articulated vehicle accident cases show that certain collision sequence of events and specific road and environmental conditions occur together with regular frequency. Trailer yaw, vehicle jacknife, run-off-road events are commonly associated with high, variable winds, icy road conditions, and empty to partially loaded trailers (Figure C19). Accident cases were grouped into three main classes, namely, 1) wind driven instability, 2) single vehicle cases, and 3) two or more vehicles involved (Figure C20).

ii) Excluding wind data, accident statistics from the University of Manitoba study are comparable to a similar study conducted in Ontario [2]. In the Ontario study, 88% of accidents were coded as the driver travelling "too fast for prevailing conditions". Driver interviews conducted during the Manitoba study show that in accidents involving wind driven instability, the trailer had developed severe yaw by the time the driver was aware of the situation. Simulation tests in this study indicate that under certain conditions yaw develops so rapidly that it may not be dynamically possible to correct the instability.

Current on-site accident data forms in many police jurisdictions were designed for expediency in gathering data and for ease of computer input. Without allowing detailed data collection, such forms may wrongly cause drivers to be blamed for accidents in which they may have little or no control over.

iii) A simple dynamic model consisting of a second order differential equation describing articulated vehicle behavior was developed and exhibits the qualitative aspects of trailer behavior without using the more complex models [3,4].

iv) Wind gust has more of an influence on vehicle instability than wind magnitude. A high wind with no gust can be considered essentially static, while wind gust provides dynamic energy input to an oscillating trailer. The simulation of a trailer on a snow packed surface is shown to increase trailer yaw by 2.2 degrees for every 10 MPH increase in wind. For wind gust, trailer yaw increases by 6.9 degrees for every 10 MPH increase in gust.

v) The use of brake action on an icy road to correct a trailer in yaw is proven to aggravate instability. This is due to the loss of lateral friction forces as a tire glides across an icy surface creating a microfilm of water at the tire/ice interface, and thus creating a lubricated surface. Restoring a trailer in yaw can be accomplished by increasing speed and taking advantage of frontal aerodynamic forces. This concept is also stated by Telionis et al [31]. Road surface friction has the effect of decreasing yaw by 6 degrees for every 0.2 increase in friction from a base of 0.2. In addition, at high friction values the influence of aerodynamics between 45 and 48 foot trailers is reduced to the point where the yaw differences are negligible.

vi) Vortex shedding from the trailer is found to provide a mechanism to extract energy from a wind stream to drive the trailer in oscillation. This is accomplished when Karman vortex shedding from the rear of the trailer locks in phase with frontal wind on the body of the trailer. Trailer yaw then asymtotically increases as frontal wind strength increases. However, when trailer yaw is out of phase with Karman vortex shedding from the rear of the trailer, frontal winds act to dampen trailer yaw.

Vehicle speed is found to have a significant effect on both the Karmn vortex shedding strength and frequency and also frontal wind effects. This is due mainly to the fact that aerodynamic effects are a squared function of velocity. However, at vehicle speeds of less than 40 MPH, aerodynamic influences (including the effect of side wind) is found to have a negligible influence on trailer yaw. At low vehicle speed, trailer yaw is mainly affected by the lateral action of the trailer about its suspension roll center.

vii) For every 10,000 lb. increase in cargo weight, yaw is reduced by 2.6 degrees. This is due to the increase in the trailer mass moment of inertia and additional lateral friction at the trailer tires. At large cargo weights, trailer yaw between 45 and 48 foot trailer is negligible due to high mass inertia.

viii) Trailer suspension influence is found to have a decreasing effect on lateral forces as spring stiffness increases This is due to the reduction in lateral motion of the suspended trailer mass about the suspension roll center. Although increasing cargo weight influences lateral motion of the suspended trailer mass about the suspension roll center, this is due to the effect increasing mass has on roll frequency. The spring constant K remains the same under all mechanical, cargo, and environmental conditions.

xi) In conclusion, this work demonstrates that under certain environmental conditions, articulated commercial vehicles are inherently unstable in such a way that they may be dynamically impossible for drivers to correct. Therefore, a percentage of articulated vehicle accidents are unpreventable. However, this percentage for the Province of Manitoba cannot be determined from the limited number of cases recorded. Present accident recording forms are not formatted to reflect the possibility of "dynamic failure" of this vehicle system, and therefore accidents are coded to reflect the driver travelling too fast for conditions. The inherent unpredictability of articulated vehicles under certain weather and load conditions renders it impossible for a driver to determine a safe speed.

REFERENCES


1) Hauer, E. "Reflections on Methods of Statistical Inference in Research on the Effect of Safety Counter-Measures", Accident Analysis and Prevention, Vol. 15, No. 4, 1983, pp. 275-285.

2) Billing, A.M., and M. Wolkowicz. "Commercial Vehicle Accident An On-the-Scene Study" ,Report No. RR-235. Downsview, Ontario: Ministry of Transporation and Communications, 1982.

3) Martinez, J., and J. Wallingford. "Computer-Aided Accident Reconstruction of Tractor-Semitrailers", SAE paper no. 851529.

4) Computer Simulation of Heavy Vehicle Dynamic Behavior: User's Guide to the UMTRI Models. Interim Technical Report no. 3. Vehicle Weights and Dimensions Study. Roads and Transportation tion Assocation of Canada, June, 1985.

5) James M., G. Smith, and J. Wolford. Applied Numerical Methods for Digital Computation with Fortran and CSMP. New York: Harper and Row, 1977, pp. 397-418.

6) Griffiths, W.M., and R. Parker. "Low Frequency Reasonance in Wake Shedding From Parallel Plates", Journal of Sound and Vibration, Vol. 3, No. 3, 1968, pp. 371-379.

7) Arie, M., and S. Hiroshi. "Vortex Shedding for a Rectangular Prism and a Circular Cylinder Placed Vertically in a Turbulent Boundary Layer", Journal of Fluid Mechanics , Vol. 126, 1983, pp. 147-165.

8) Williamson, C. "Evolution of a Single Wake Behind a Pair of Bluff Bodies", JFM, Vol. 159, 1985, pp. 1-18.

9) Riley, N. "The Steady Streaming Induced by a Vibrating Cylinder" JFM, Vol. 68, Part 4, 1975, pp. 801-812.

10) Bearman, P.W. "On Vortex Shedding from a Circular Cylinder in the Critical Reynolds Number Regime", JFM, Vol.37, Part 3, 1969, pp. 577-585.

11) Parker, R. "Reasonance Effects in Wake Shedding from Parallel Plates: Calculation of Resonant Frequencies", JSV, Vol. 5, No. 2, 1967, pp. 330-343.

12) --------. "Resonance Effects in Wake Shedding from Parallel Plates: Some Experimental Observations", JSV, Vol.4, No.1, 1966, pp. 62-72.

13) Nakamura, Y., and M. Nakashima. "Vortex Excitation of Prisms with Elongated Rectangular, H and -- Cross-sections, JFM, Vol. 163, 1986, pp. 149-169.

14) Griffin, O., and C. Votaw. "The Vortex Street in the Wake of of a Vibrating Cylinder", JFM, Vol.51, Part no.1, 1973, pp. 31-48.

15) Koopmann, G. "The Vortex Street of Vibrating Cylinders at Low Reynolds Numbers", JFM, Vol.28, Part no. 3, 1967, pp. 501-512.

16) Abernathy, F., and R. Kronauer. "The Formation of Vortex Streets", JFM, Vol.13, Part no. 1, 1962, pp. 1-21.

17) Griffin, O., and R. Skrop. "A Model for the Vortex-Excited Resonant Response of Bluff Cylinders", JSV, Vol.27, No. 2, 1973, pp. 225-235.

18) Johns, D., King, R., and M. Prosser. "Vortex Excitation of Model Bridge Piles in Water", JSV, Vol. 29, No. 2, 1973, pp. 169-188.

19) Griffin, O., and S. Ramberg. "The Vortex-Street Wakes of Vibrating Cylinders", JFM, Vol. 66, Part 3, 1974, pp. 553-576.

20) Wood, C. "The Effect of Lateral Vibrations on Vortex Shedding from Blunt-based Aerofoils", JSV, Vol. 14, No. 1, 1971, pp. 91-103.

21) Komatsu, S., and H. Kobayashi. "Vortex-Induced Oscillation of Bluff Cylinders", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 6, No. 3&4, 1980, pp. 335-362.

22) Shiraishi, N., and M. Matsumoto. "On Classification of Vortex Induced Oscillation and Its Application for Bridge Structures" JWEIA, Vol.14, No. 1&2, 1986, pp. 419-430.

23) Olivari, D.,"An Investigation of Vortex Shedding and Galloping Induced Oscillation on Prismatic Bodies", JWEIA, Vol. 11, No. 1-3, 1986, pp. 307-319.

24) Ervin, R.D.,"The Influence of Size and Weight Variables on the Roll Stability of Heavy Vehicles", SAE paper no. 831163. 1983

25) Bremer, J.,and R. Grimm. "Wheel Lock Control State of the Art" Transportation Research Record No. 621, National Academy of Sciences, 1977, pp. 83-89.

26) "Mechanics of Pneumatic Tires", Report No. DOT-HS-805-952, United States Department of Transportation, National Highway and Traffic Safety Administration, 1984, pp. 595-600.

27) Boyd, P., Hinch, J., and A. Neill. "Truck Tire Cornering and Braking Traction Study", Report No. DOT-HS-804-732, United States Department of Transportation, National Highway Traffic and Traffic Safety Administration, 1983.

28) Drive Traction Characteristics of Trucks and Truck Combinations, Western Highway Institute, 2nd Ed., 1976, pp. 36-57.

29) Moncarz, H.T., Barlow, J.B., and R.J. Hawks. "Stability and Crosswind Response of an Articulated Vehicle with Roll Freedom", Advances in Road Vehicle Aerodynamics Symposium, Paper No. 7, London, England: BHRA Fluids Engineering, 1973, pp. 101-126.

30) Dugoff, Howard. " On the Influence of Aerodynamic Moments on the Lateral Stability of Articulated Highway Vehicles", Proceedings of the First International Conference on Vehicle Mechanics, Wayne State University, Detroit, Michigan, July 16-18, 1968, pp. 215-245.

31) Telonis, A.P., Fahrner, C.J., and G.S. Jones. "An Experimental Study of Highway Interferences", JWEIA, Vol, 17, 1984, pp. 267-293.

32) Kobayashi, T., and K. Kitoh. "Cross-wind Effects and the Dynamics of Light Cars", Proceedings of an International Conference, London, England, June 16-18, 1982, Special Publication No. SP3, International Journal of Vehicle Design, 1983, pp. 142-157.

33) Chin, T. "The Influences of Road Surface Discontinuities on Safety", NRB Special Report, 1980, pp. 1-36.

34) Spath, Helmuth. Cluster Analysis Algorithms-for data reduction and classification of objects, Rexdale, Ontario: John Wiley and Sons, 1980.

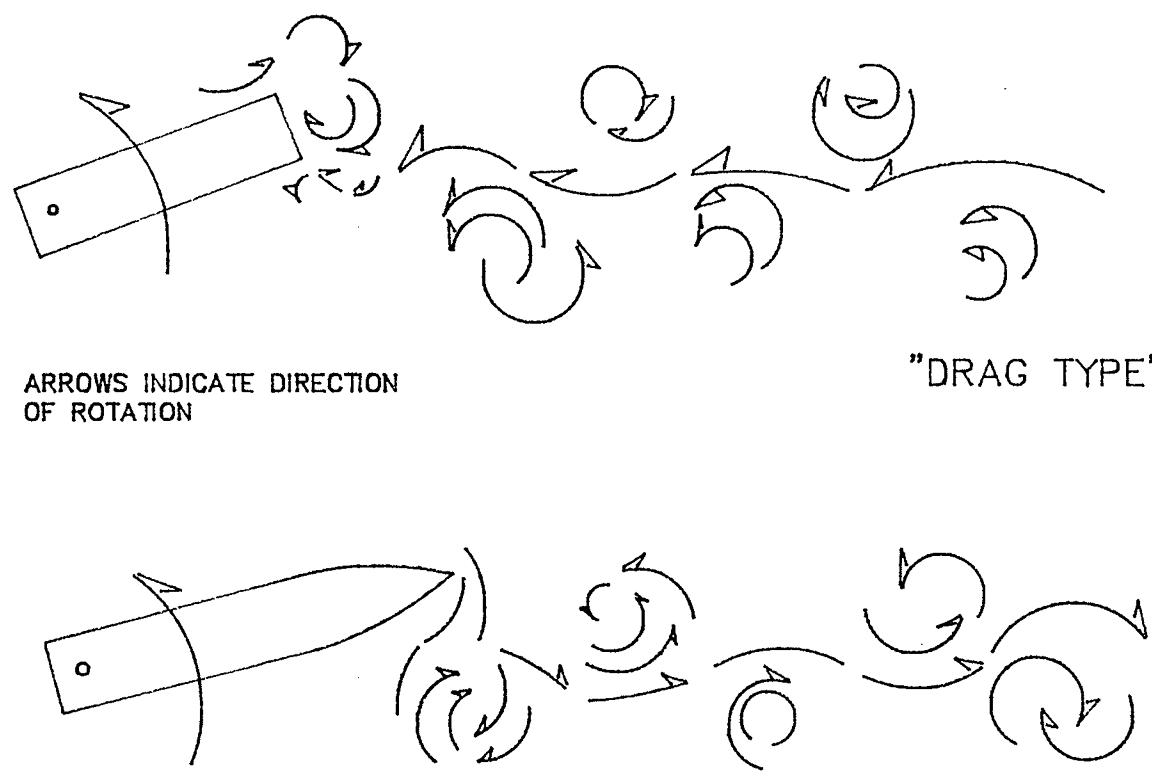
35) Statistical Analysis System (SAS). Users Guide to Statistics. Version 5. 1987.

36) Province of Manitoba 1985 and 1986 Climactic Records, Environment Canada.

# APPENDIX A

## SCHEMATICS FOR MODEL DEVELOPMENT

# FIGURE A-1



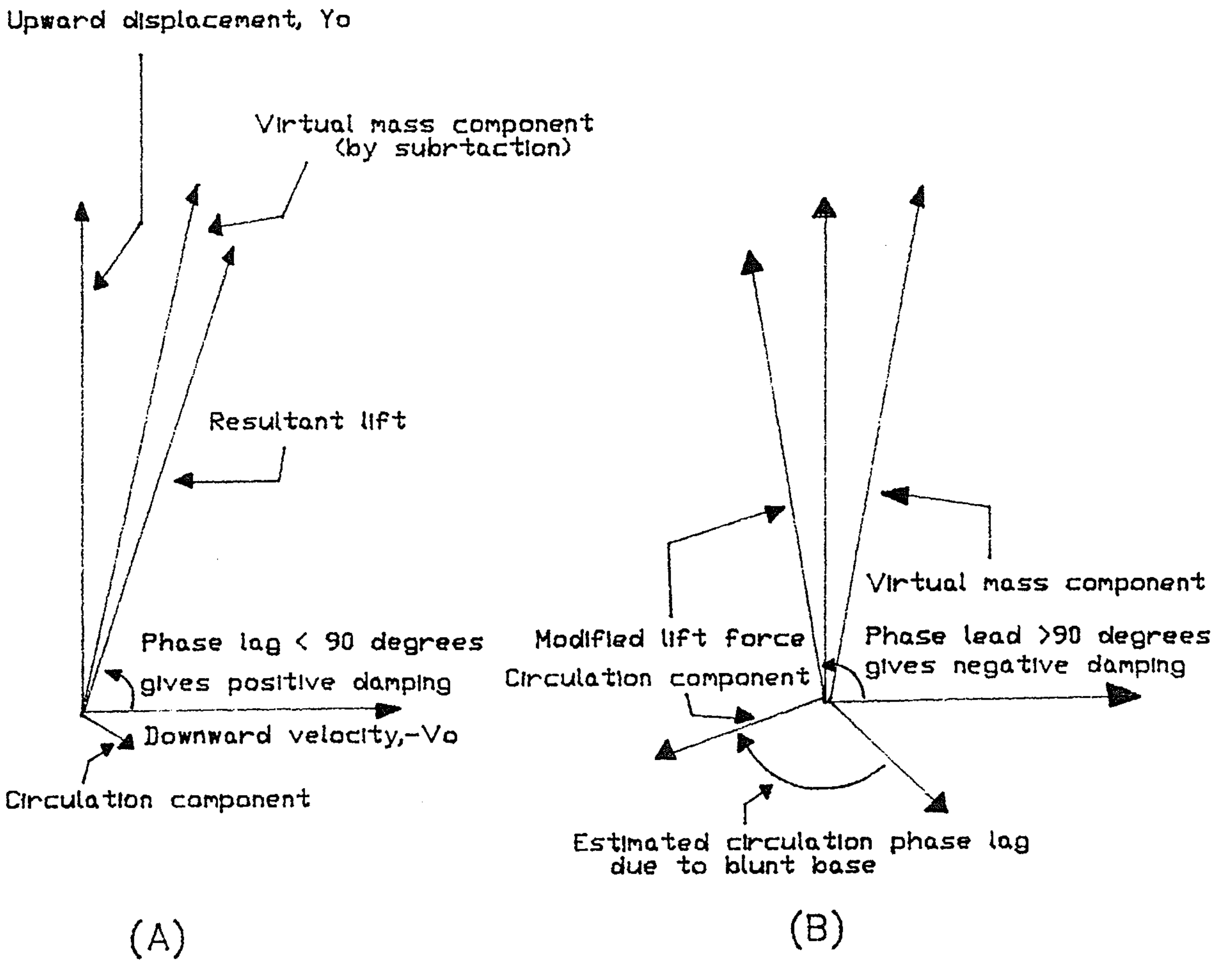
ARROWS INDICATE DIRECTION
OF ROTATION

"DRAG TYPE" VORTEX TRAIL

"THRUST TYPE" VORTEX TRAIL

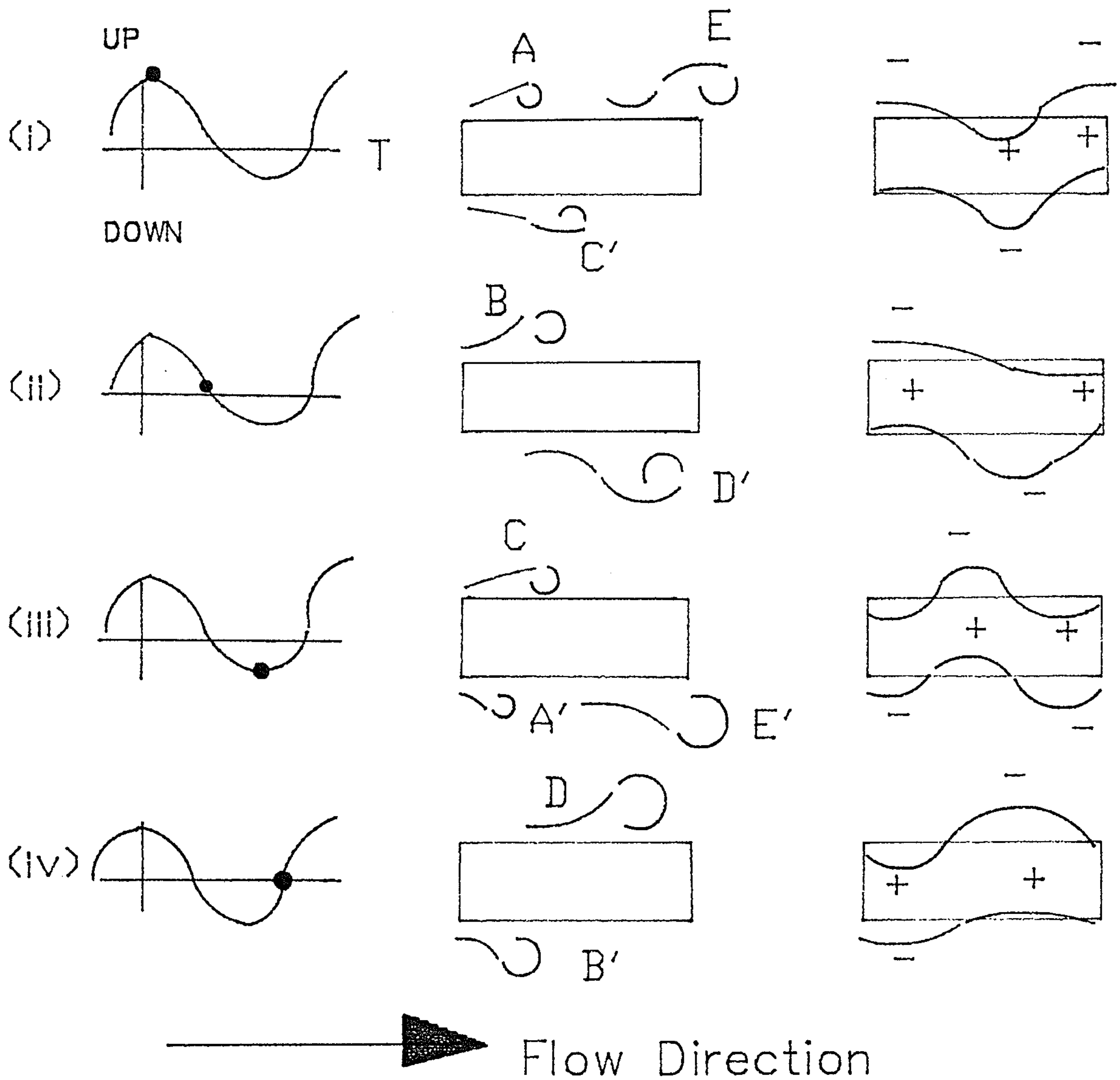
[SOURCE: WOOD]

FIGURE A-2




[SOURCE: WOOD]

# FIGURE A-3




(a) Position of cylinder (b) Location of vortex (c) Pressure distribution

[SOURCE: KOMATSU & KOBAYASHI]

# FIGURE A-4

## FORCE AND MOMENT SCHEMATIC

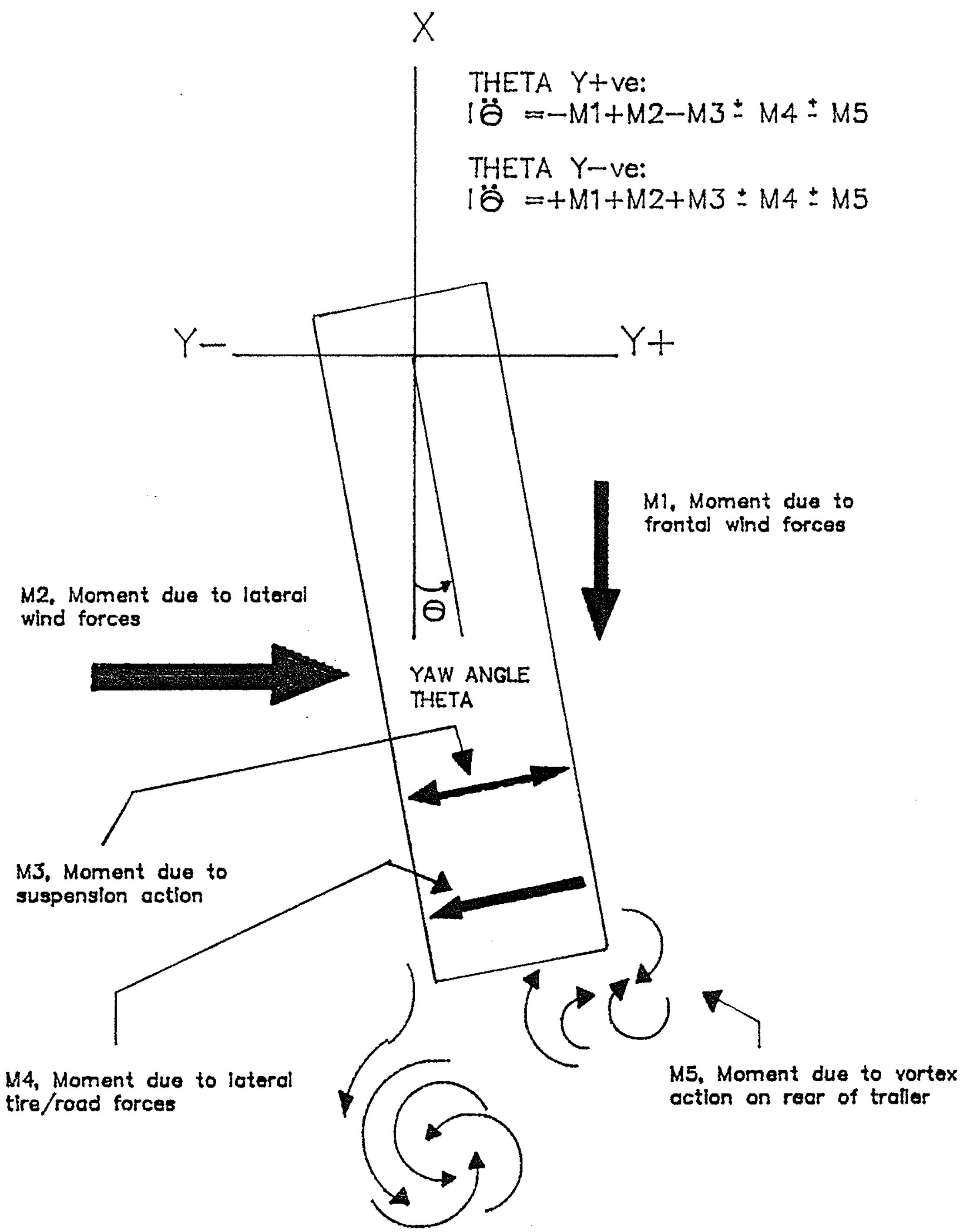
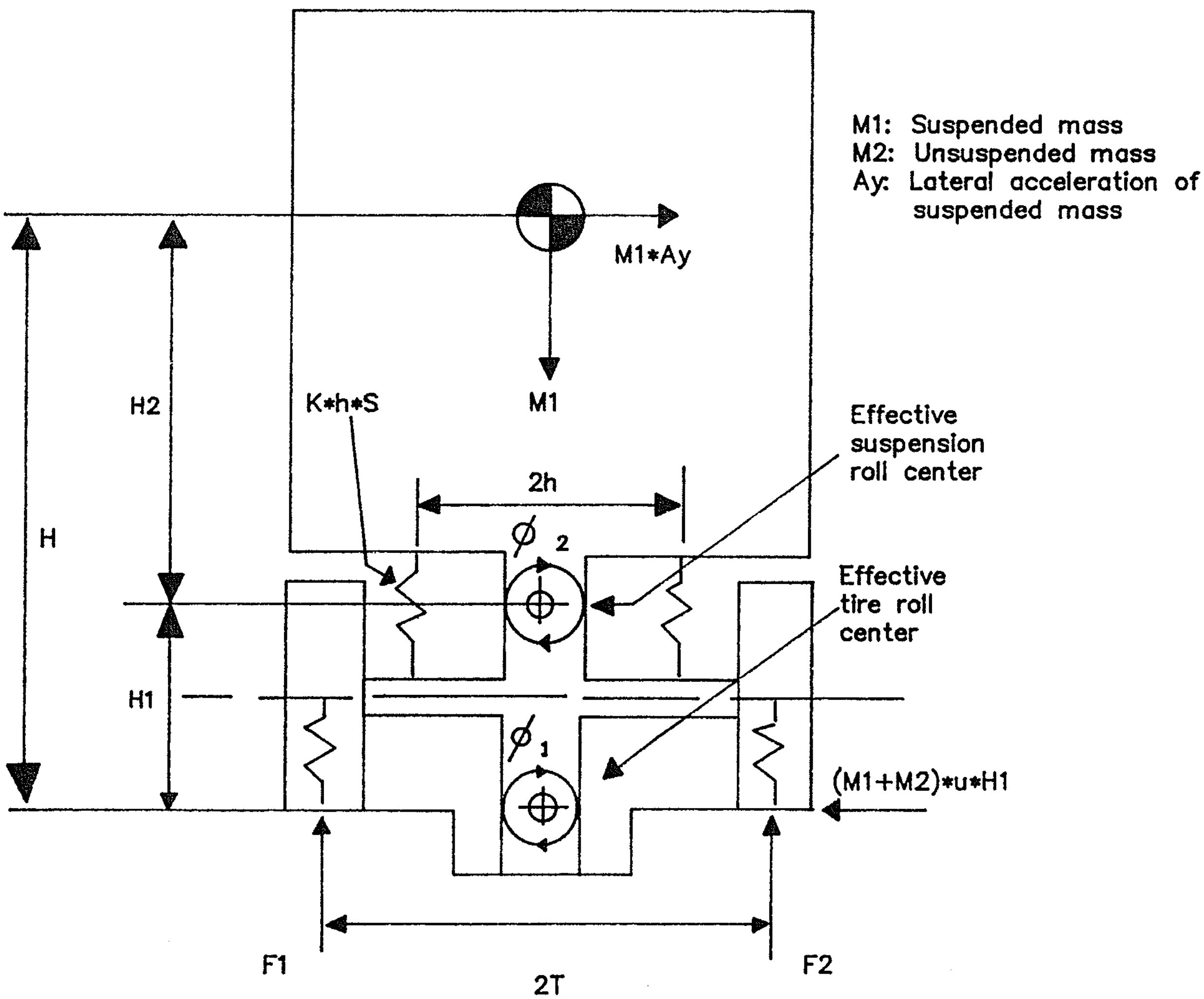


FIGURE A-5




[SOURCE: ERVIN]

# FIGURES A6 & A7

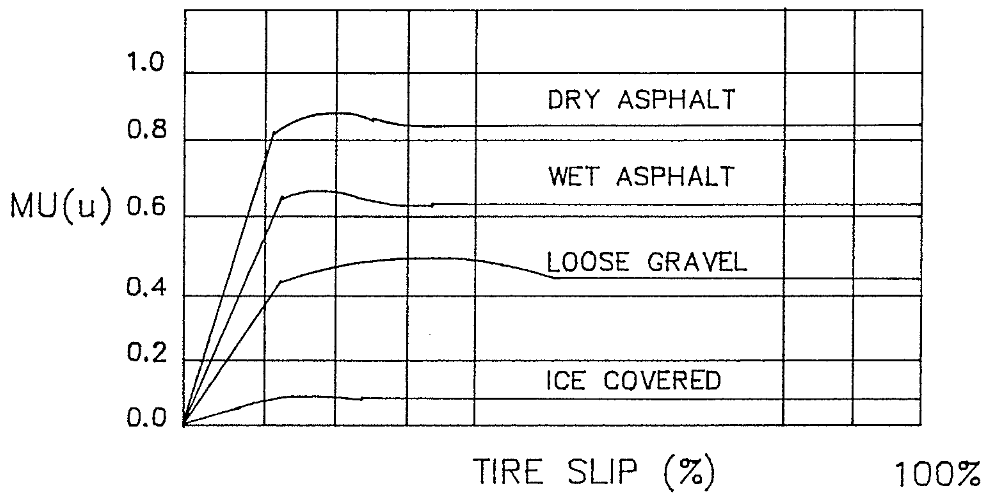



FIGURE A6: SURFACE VARIATION OF TIRE BRAKING FORCE CHARACTERISTICS

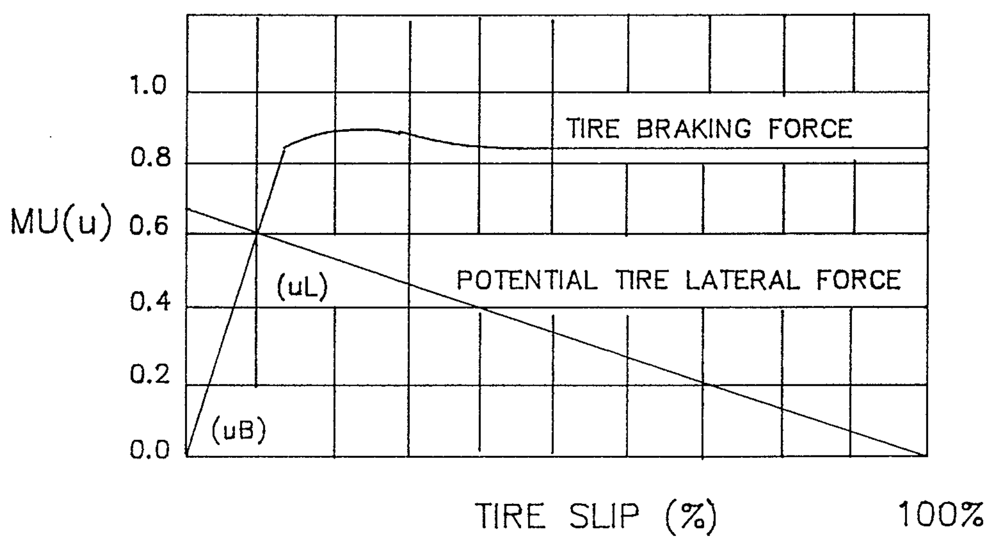



FIGURE A7: TIRE LATERAL AND BRAKING FORCE CHARACTERISTICS

[SOURCE: BREMER & GRIMM]

# APPENDIX B

## <u>MODEL SIMULATION OUTPUT</u>

FIGURE B-1

AVERAGE MAXIMUM YAW ANGLE VS. WIND SPEED

MU=0.35 (LOOSE SNOW), GUST=0, CARGO=0

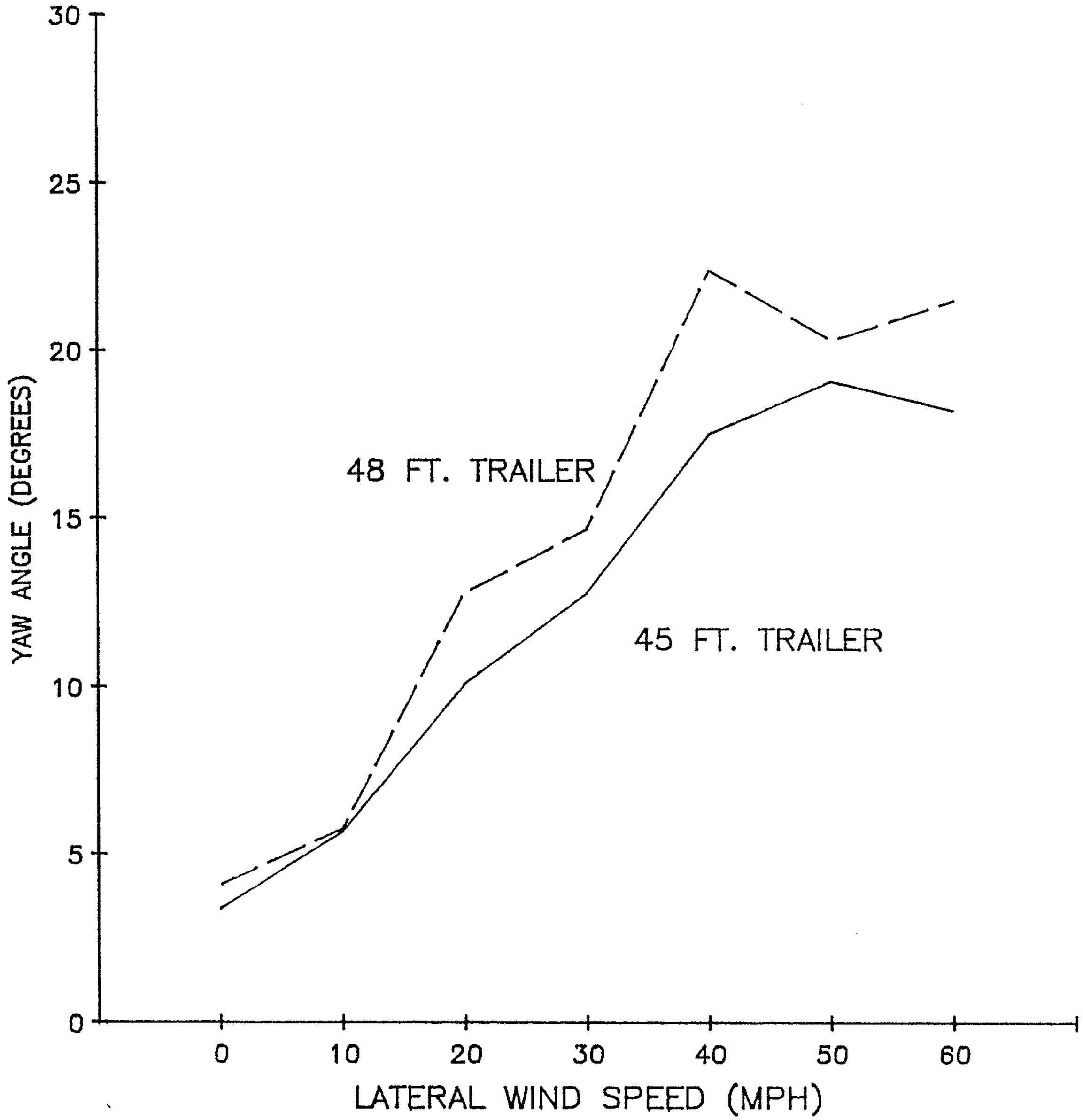


FIGURE B-2
MAXIMUM YAW ANGLE VS. WIND GUST
MU=0.35 (LOOSE SNOW), CARGO=0
BASE WIND VELOCITY=15 MPH

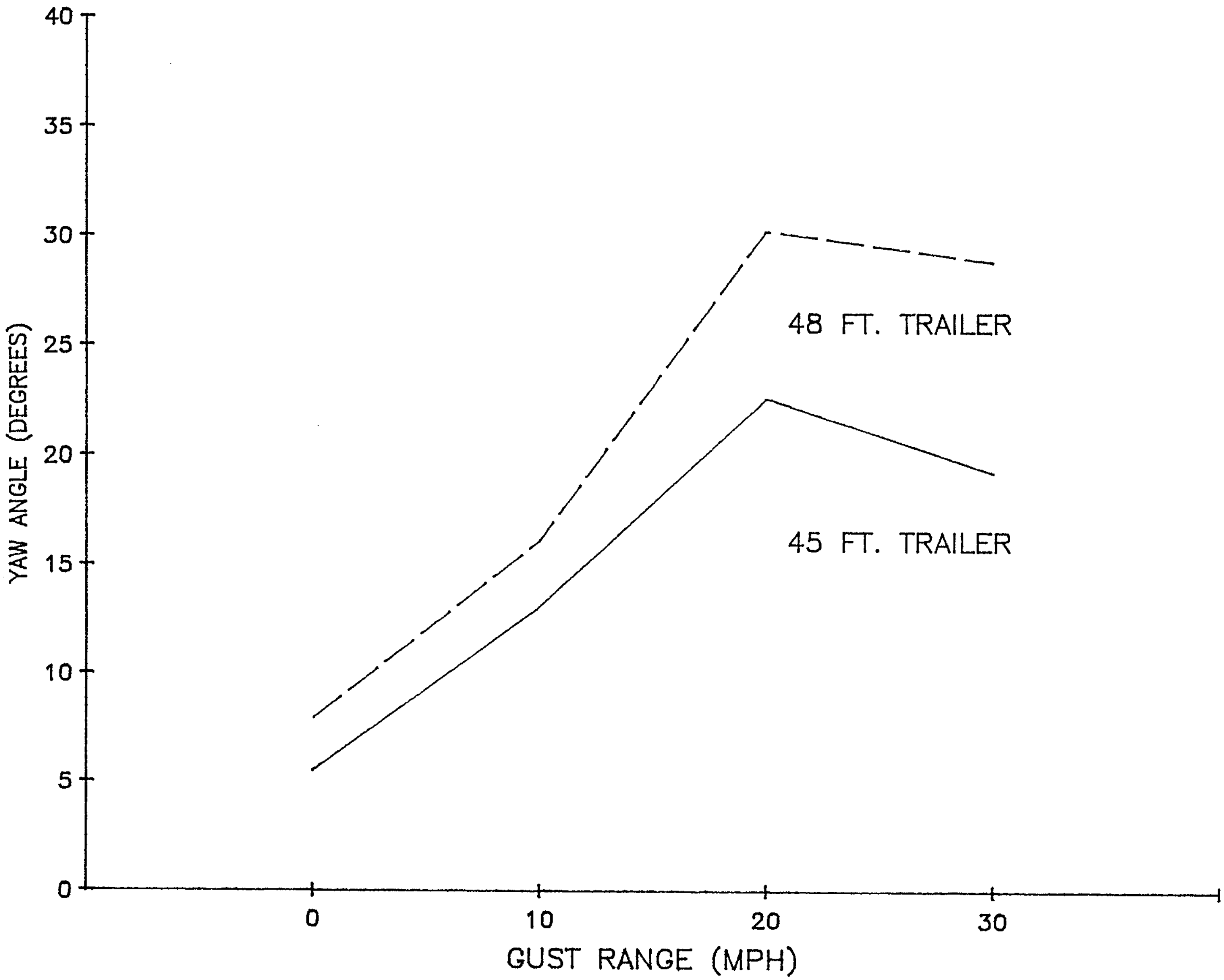


FIGURE B-3

YAW ANGLE VS. WIND GUST

MU=0.35,CARGO=0,TRAILER=45 FT.,VEL.=60 MPH

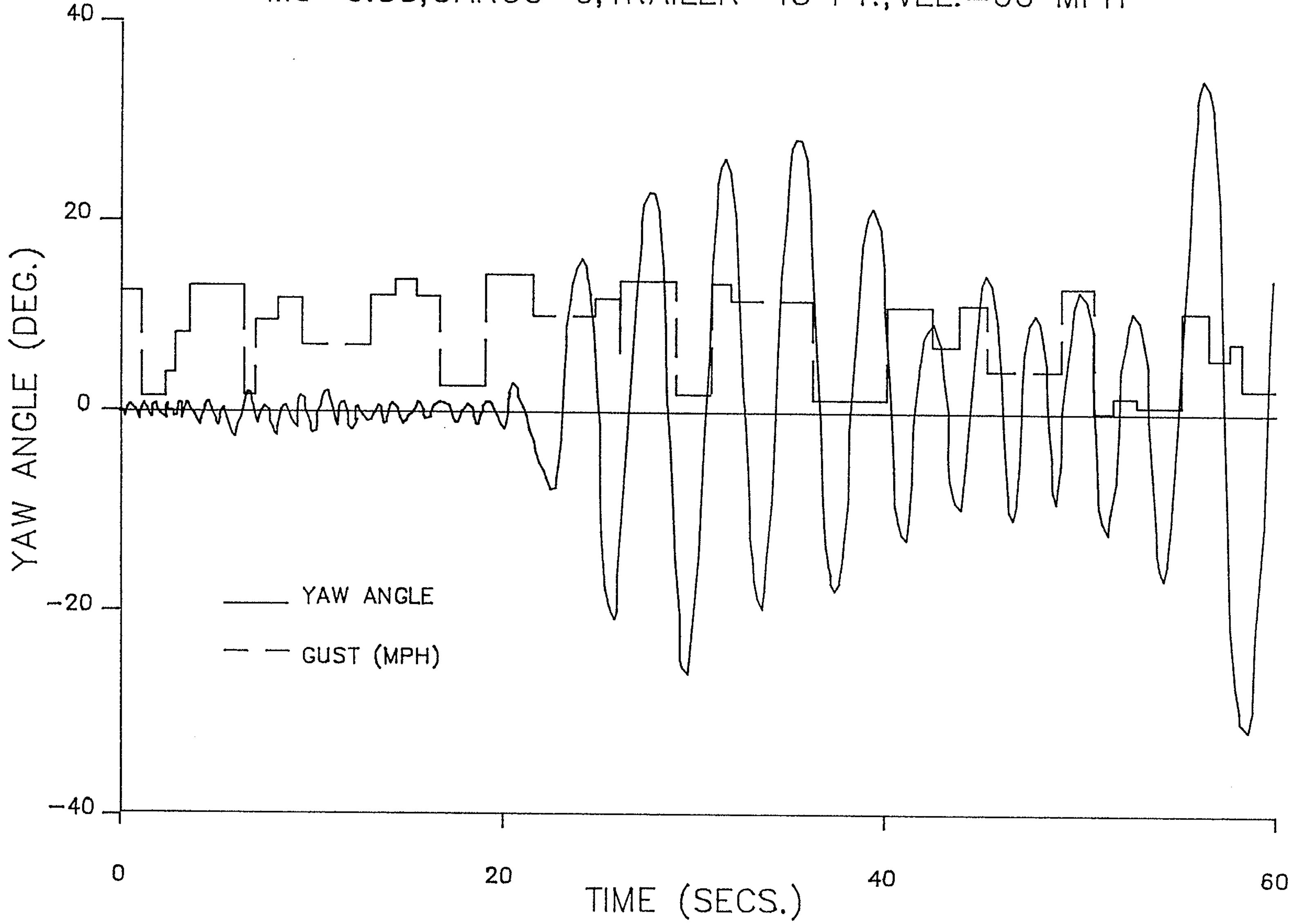


FIGURE B-4
MAXIMUM YAW ANGLE VS. WIND ANGLE
MU=0.35, GUST=0, WIND=20 MPH

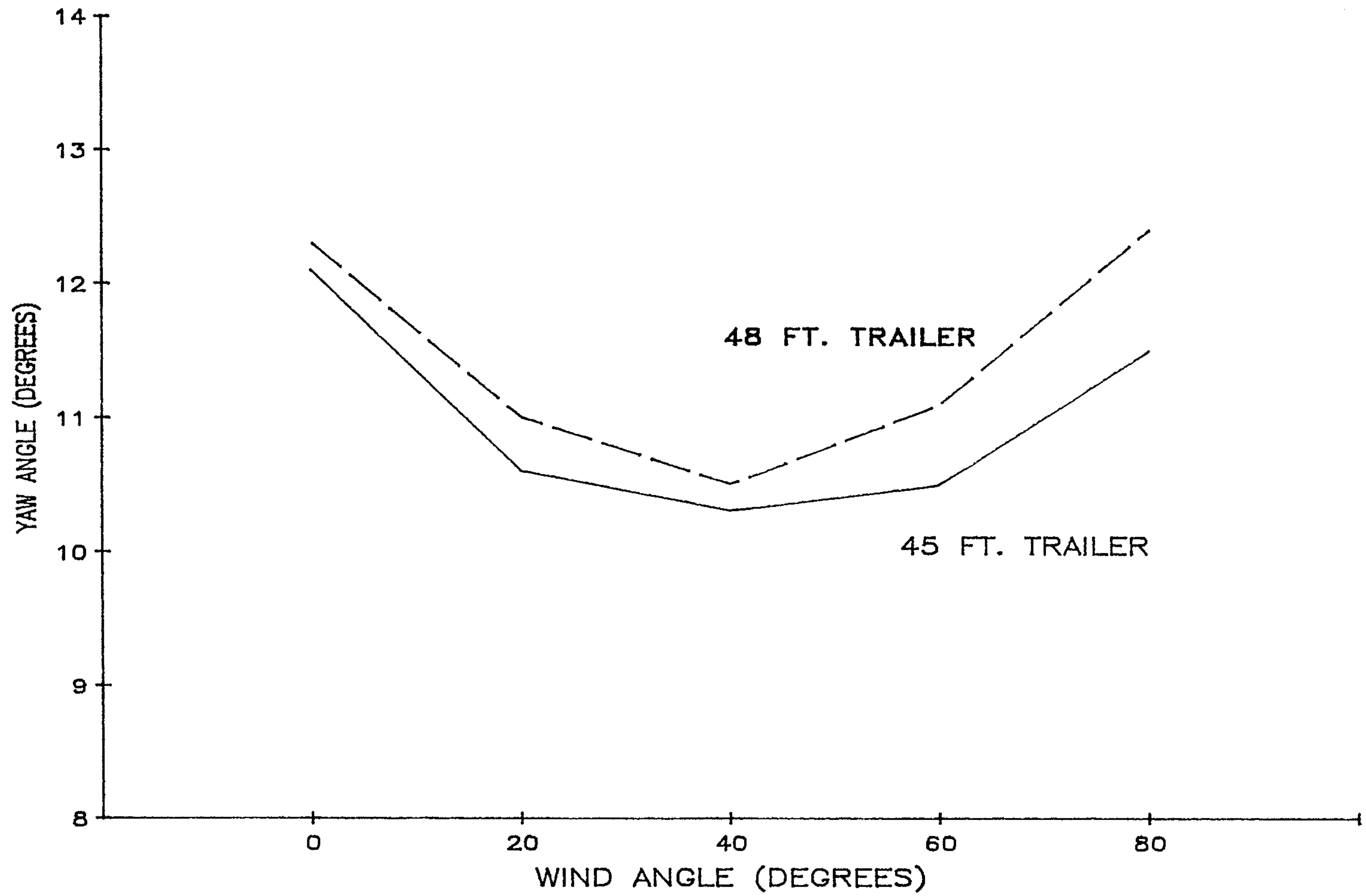
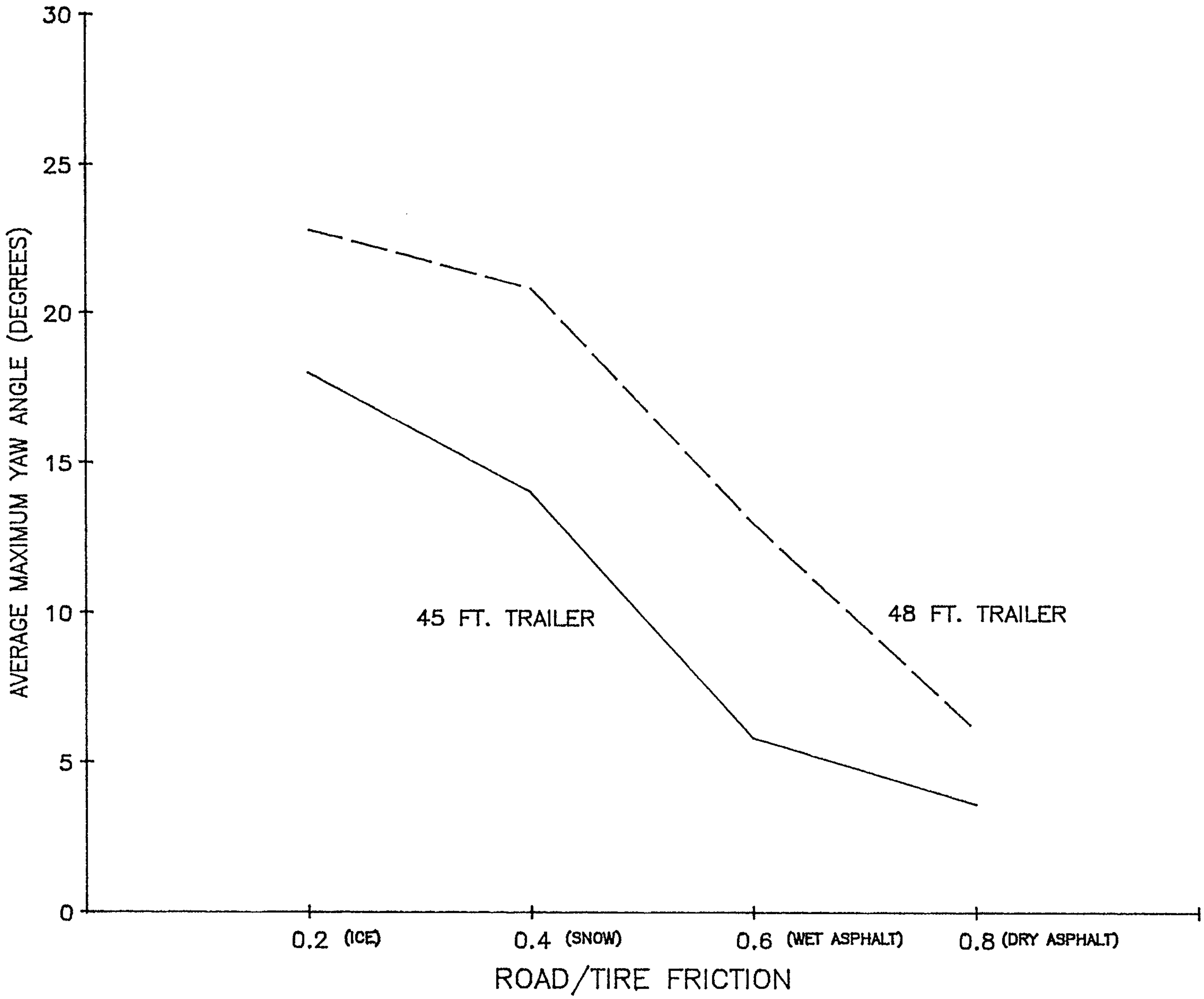


FIGURE B-5
AVERAGE MAXIMUM YAW ANGLE VS. ROAD FRICTION (MU)
CARGO=0, GUST=0, WIND=20 MPH, VEHICLE SPEED=60 MPH



# FIGURE B-6

COMPARISION OF YAW FOR ICY/DRY ROADS
CARGO=0,TRAILER=45 FT.,SPEED=60 MPH,WIND= 20 MPH

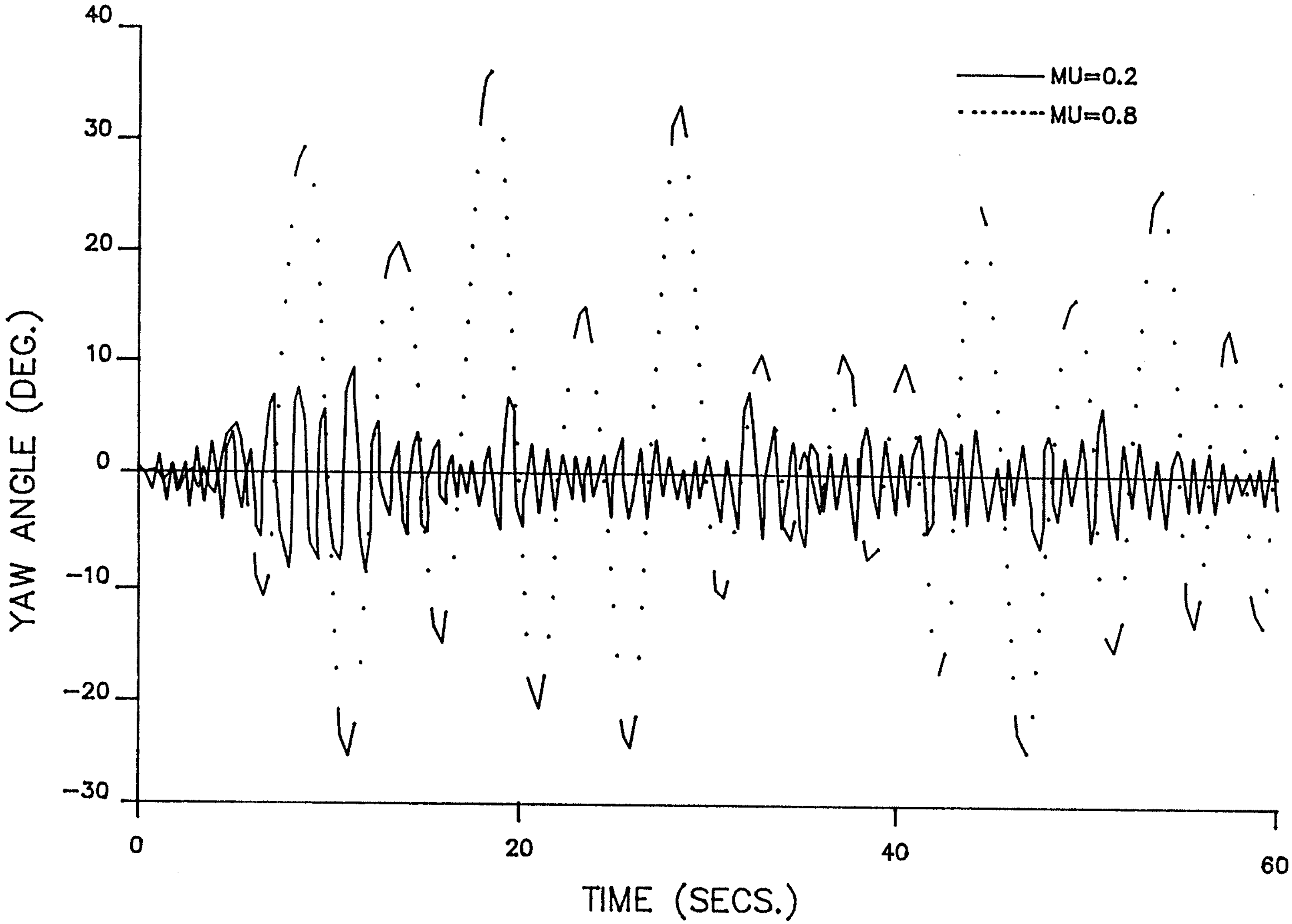


FIGURE B-7

YAW ANGLE VS. TIME
(Trailer brake lock at T=40 secs.)
MU=0.35, TRAILER=45. FT., CARGO=GUST=0

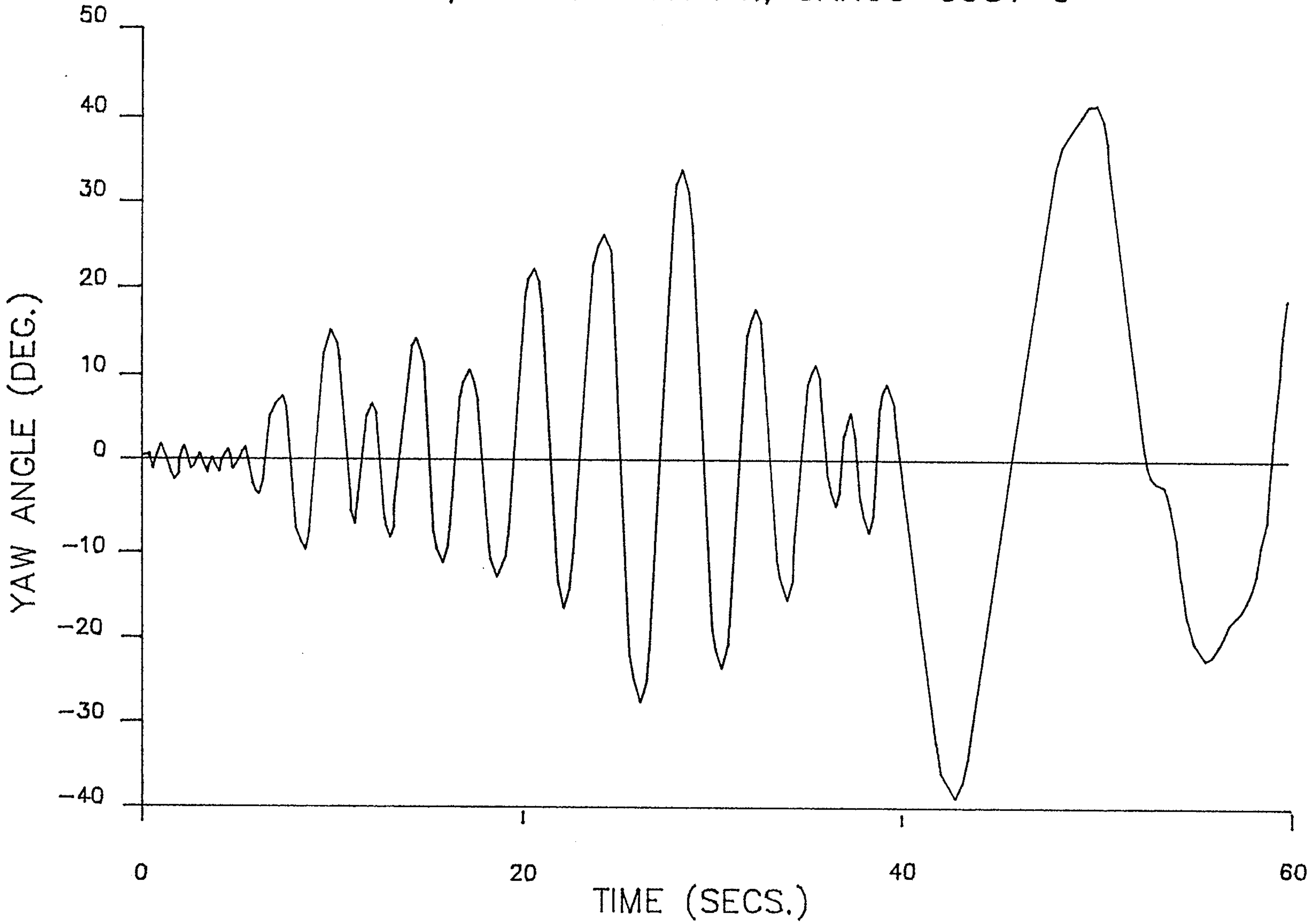


FIGURE B-8
AVERAGE MAXIMUM YAW ANGLE VS. VEHICLE SPEED
MU=0.35, WIND=20 MPH, GUST=CARGO=0

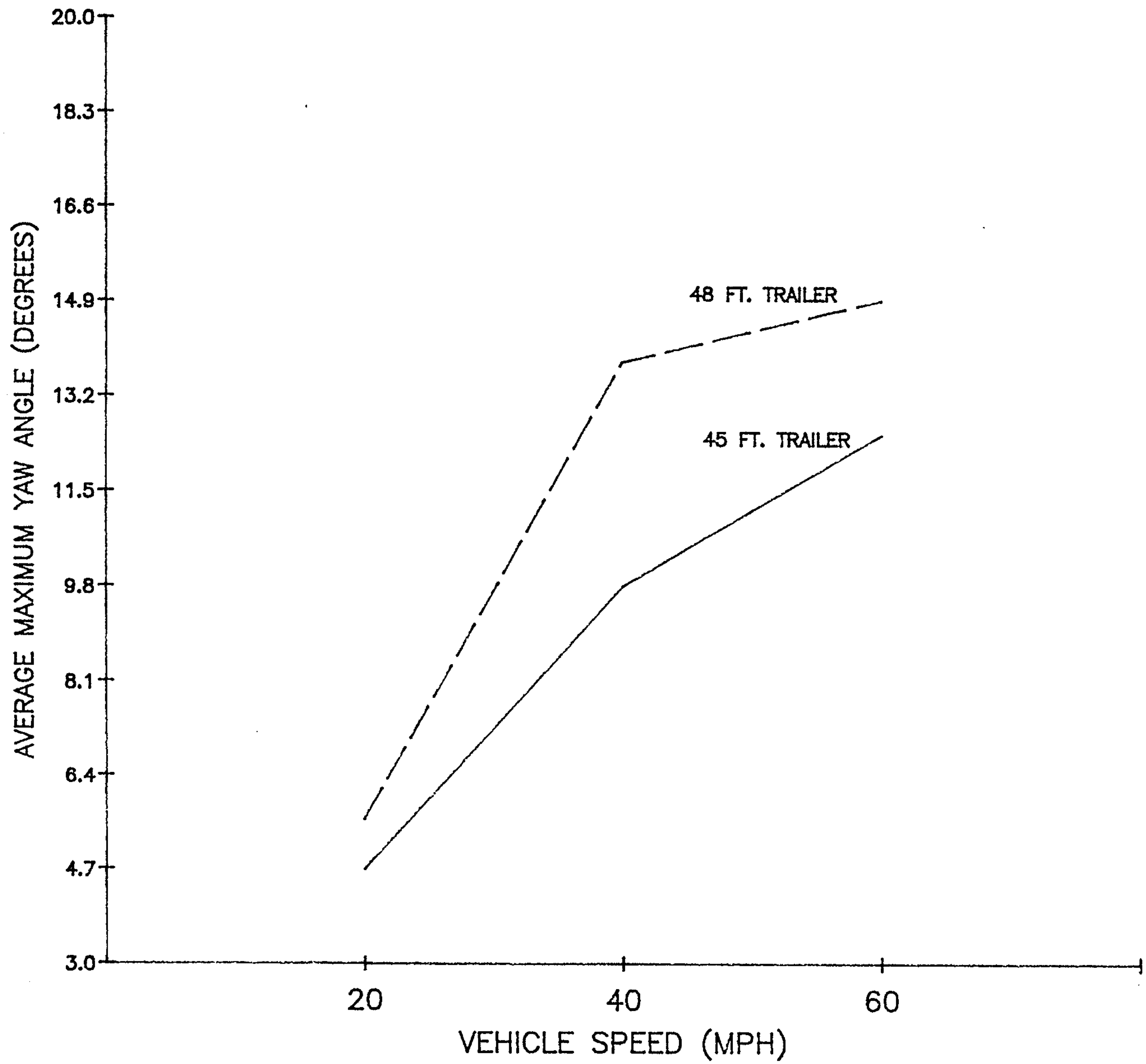


FIGURE B-9
MAXIMUM FRONTAL AERODYNAMIC MOMENTS VS. VEHICLE SPEED
(FRONTAL AND VORTEX SHEDDING MOMENTS)
MU=0.35, WIND=20 MPH, GUST=0, CARGO=0

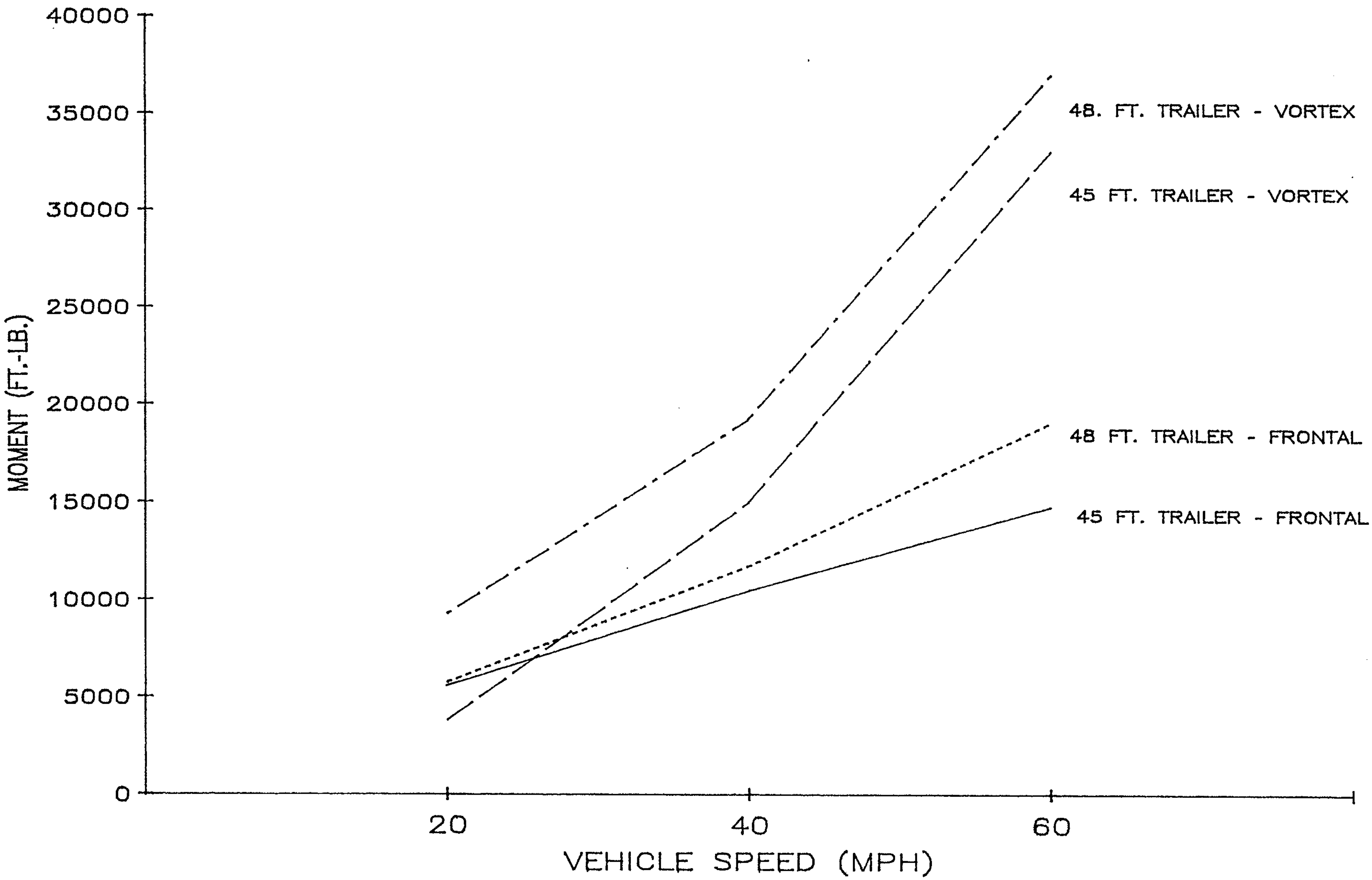
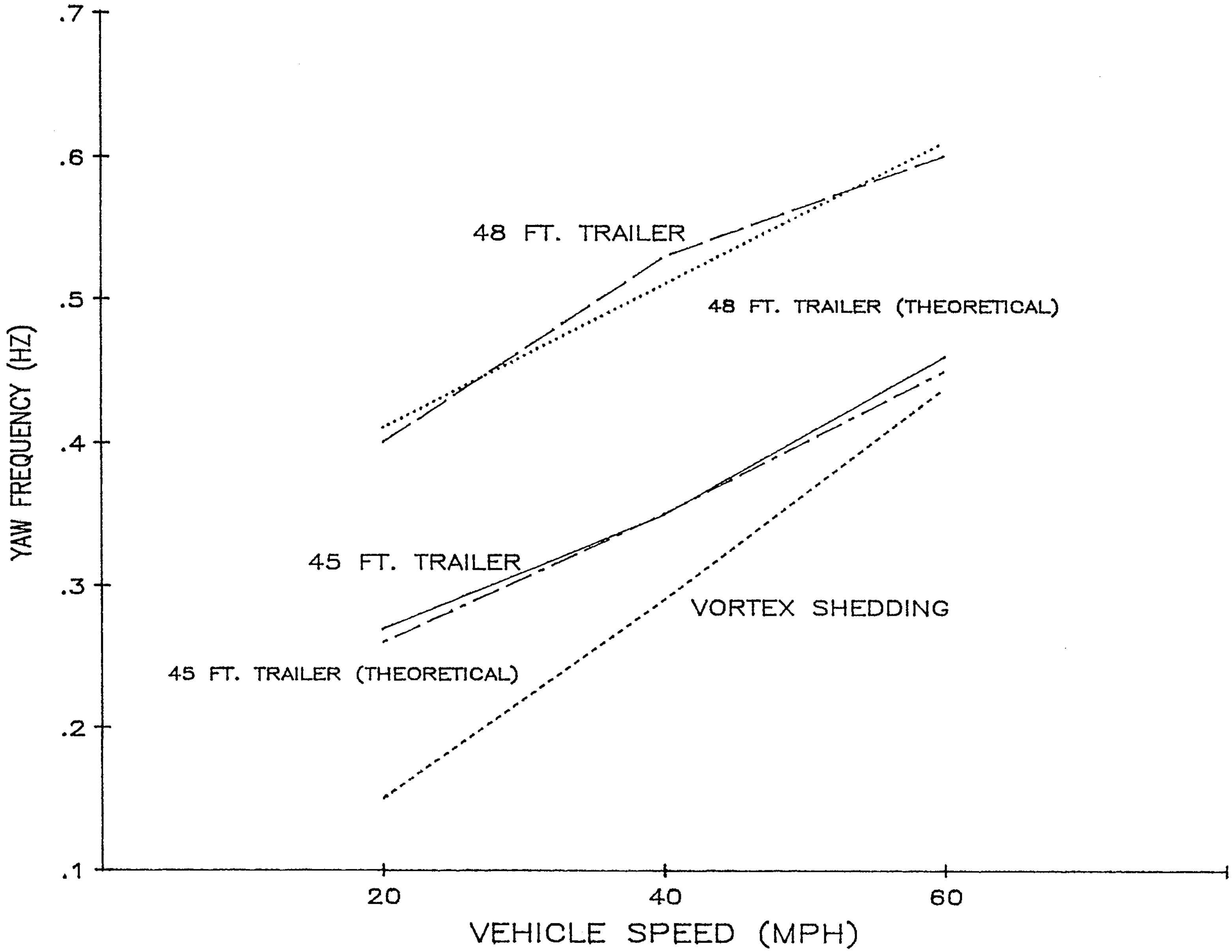
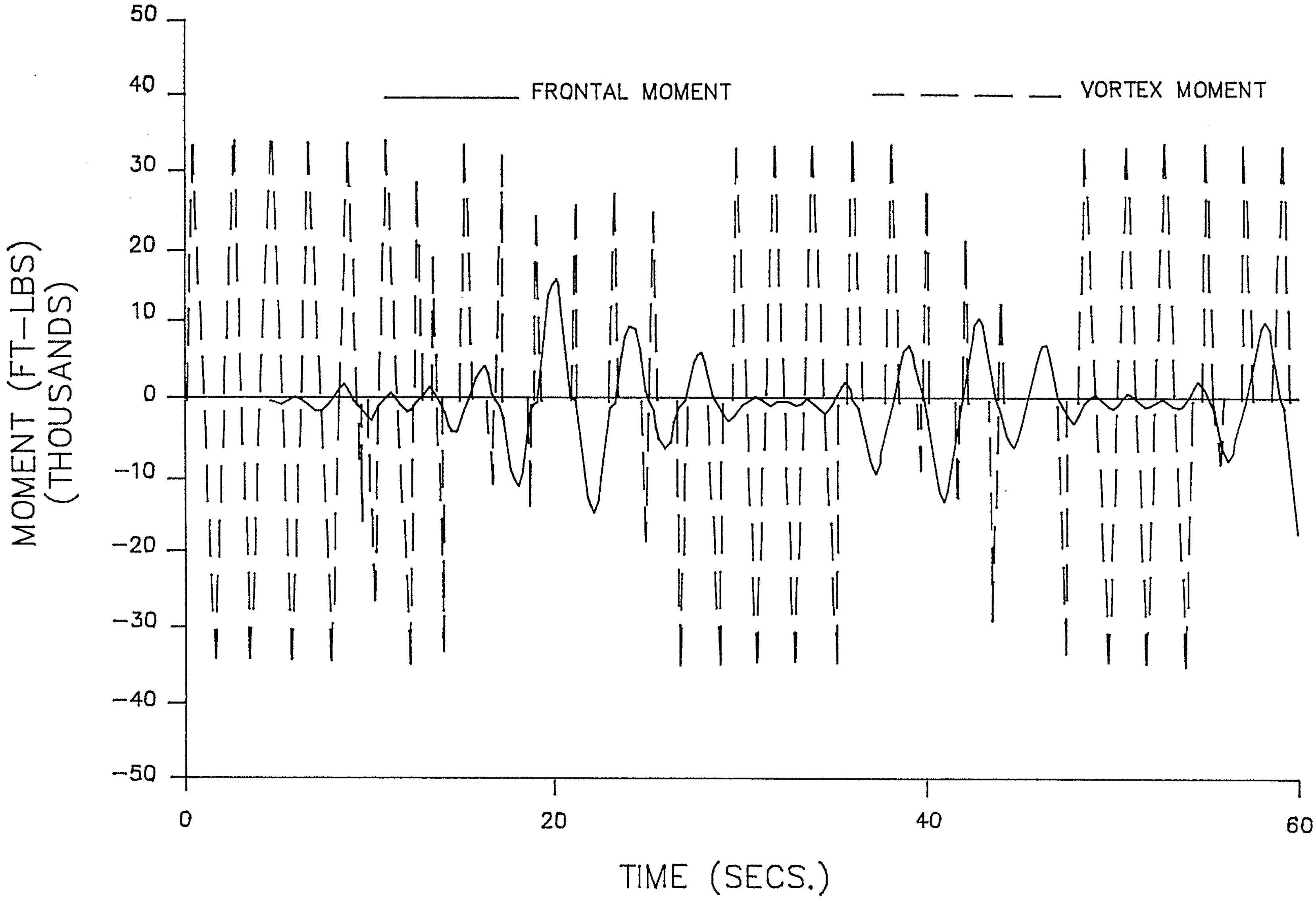


FIGURE B-10
YAW FREQUENCY (HZ) VS. VEHICLE SPEED (MPH)
MU=0.35, WIND=20 MPH, GUST=CARGO=0



# FIGURE B-11

NON-DIVERGENT FRONTAL & VORTEX MOMENTS VS. TIME
MU=0.35, TRAILER=45. FT., CARGO=GUST=0



# FIGURE B-12

DIVERGENT FRONTAL & VORTEX MOMENTS
MU=0.35,TRAILER=45 FT., CARGO=GUST=0

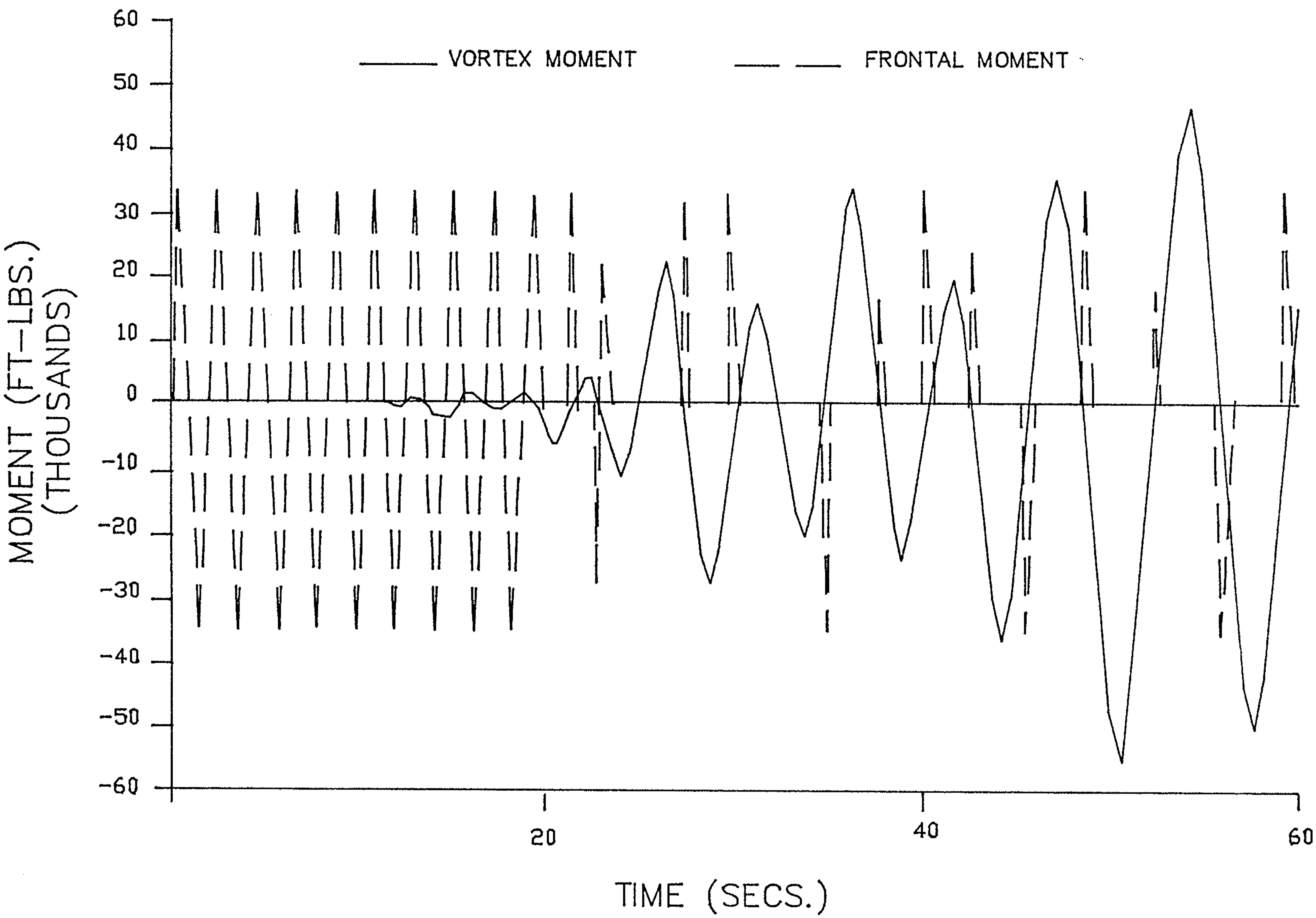
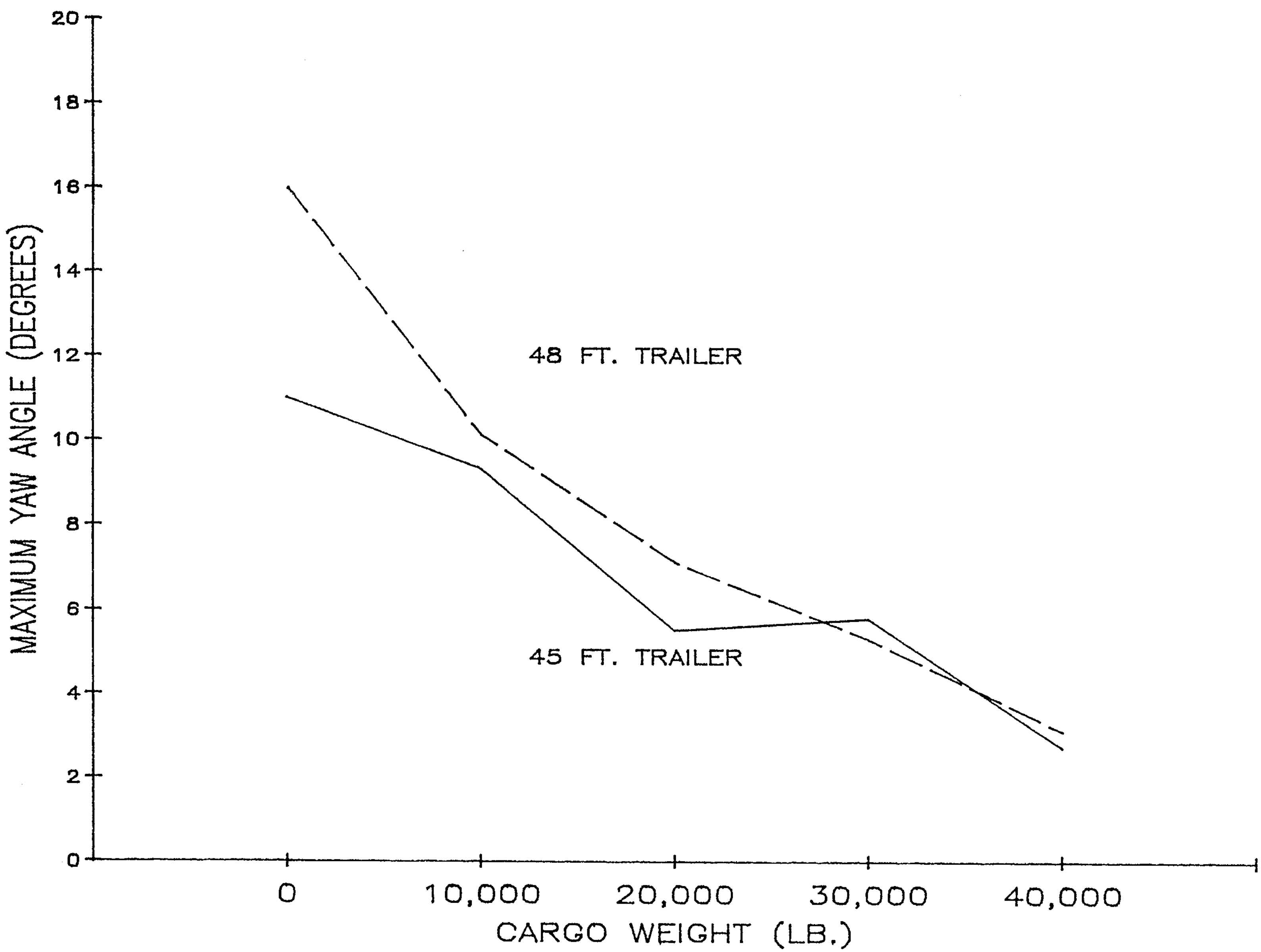


FIGURE B-13

AVERAGE MAXIMUM YAW ANGLE VS. CARGO WEIGHT

MU=0.35, WIND=20 MPH, GUST=0



# FIGURE B-14
YAW FREQUENCY (HZ.) VS. CARGO WEIGHT (LB.)
GUST=0 MPH,MU=0.35,WIND= 20 MPH

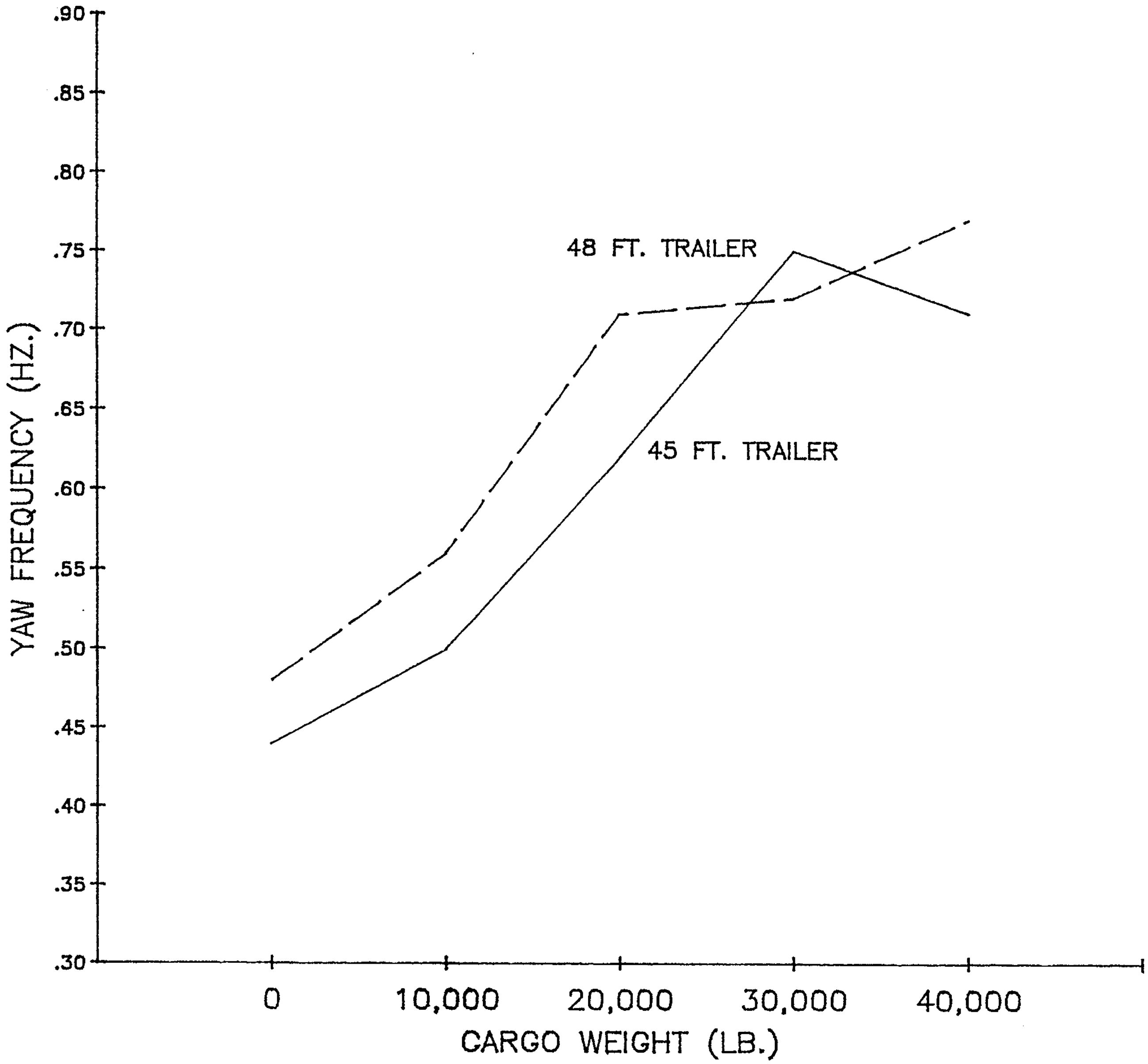
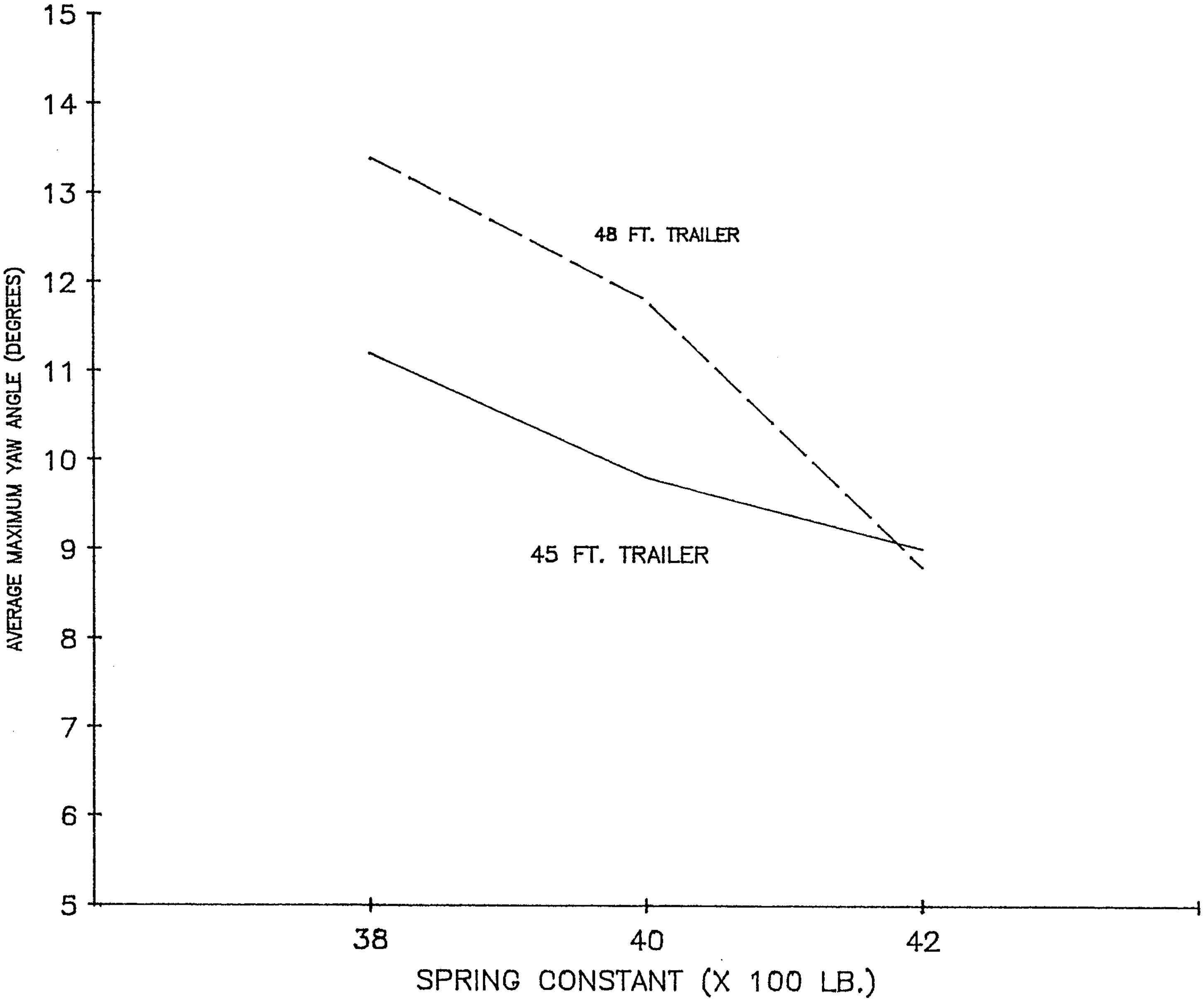


FIGURE B-15
AVERAGE MAXIMUM YAW ANGLE VS. SPRING CONSTANT
MU=0.35, WIND=20 MPH, GUST=0, VEHICLE SPEED=60 MPH



# APPENDIX C

## ACCIDENT DATA AND SAS OUTPUT

FIGURE C-1
CRITERIA VEHICLE IN COLLISION WITH...

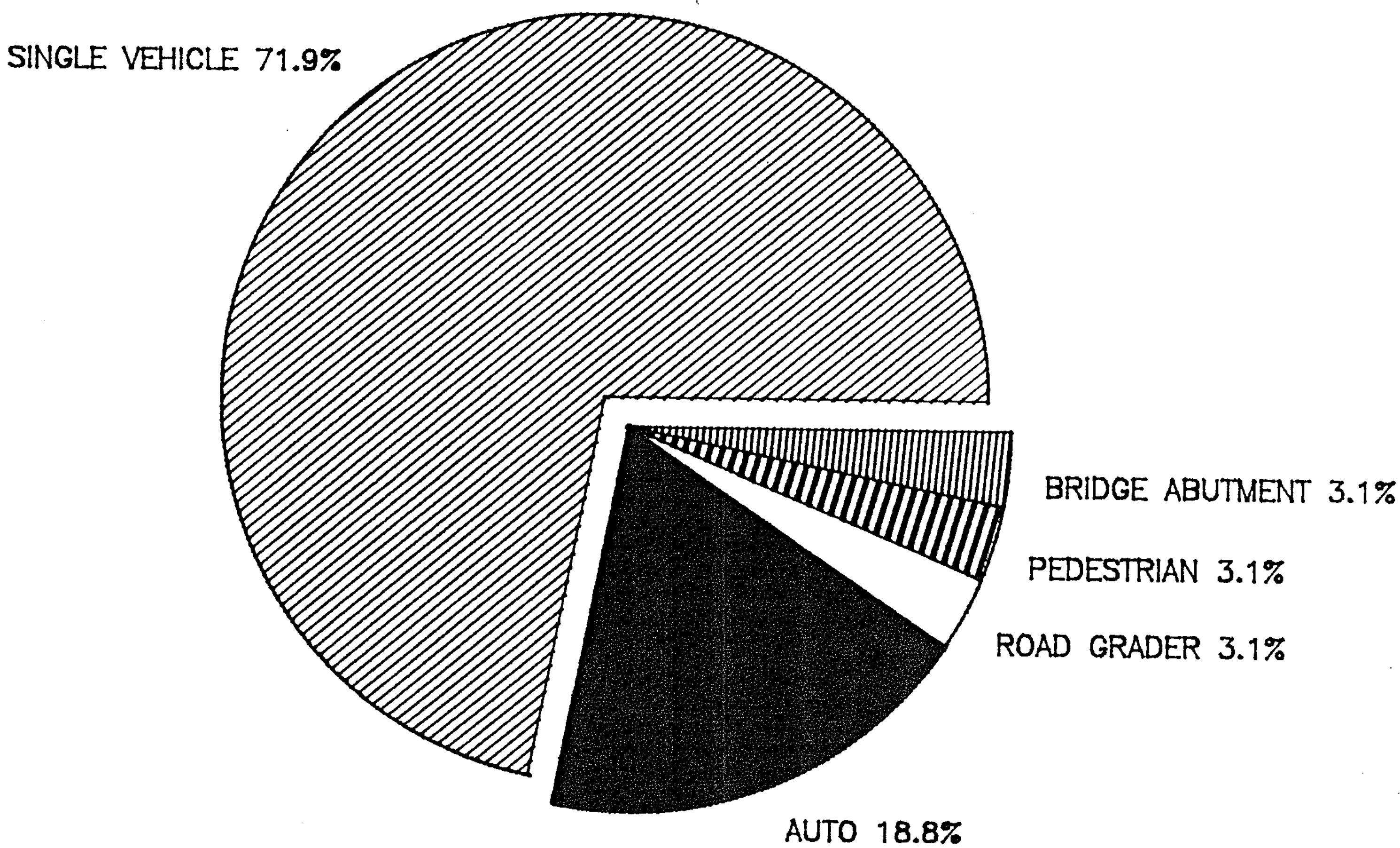


FIGURE C-2
CRITERIA VEHICLE CONFIGURATION

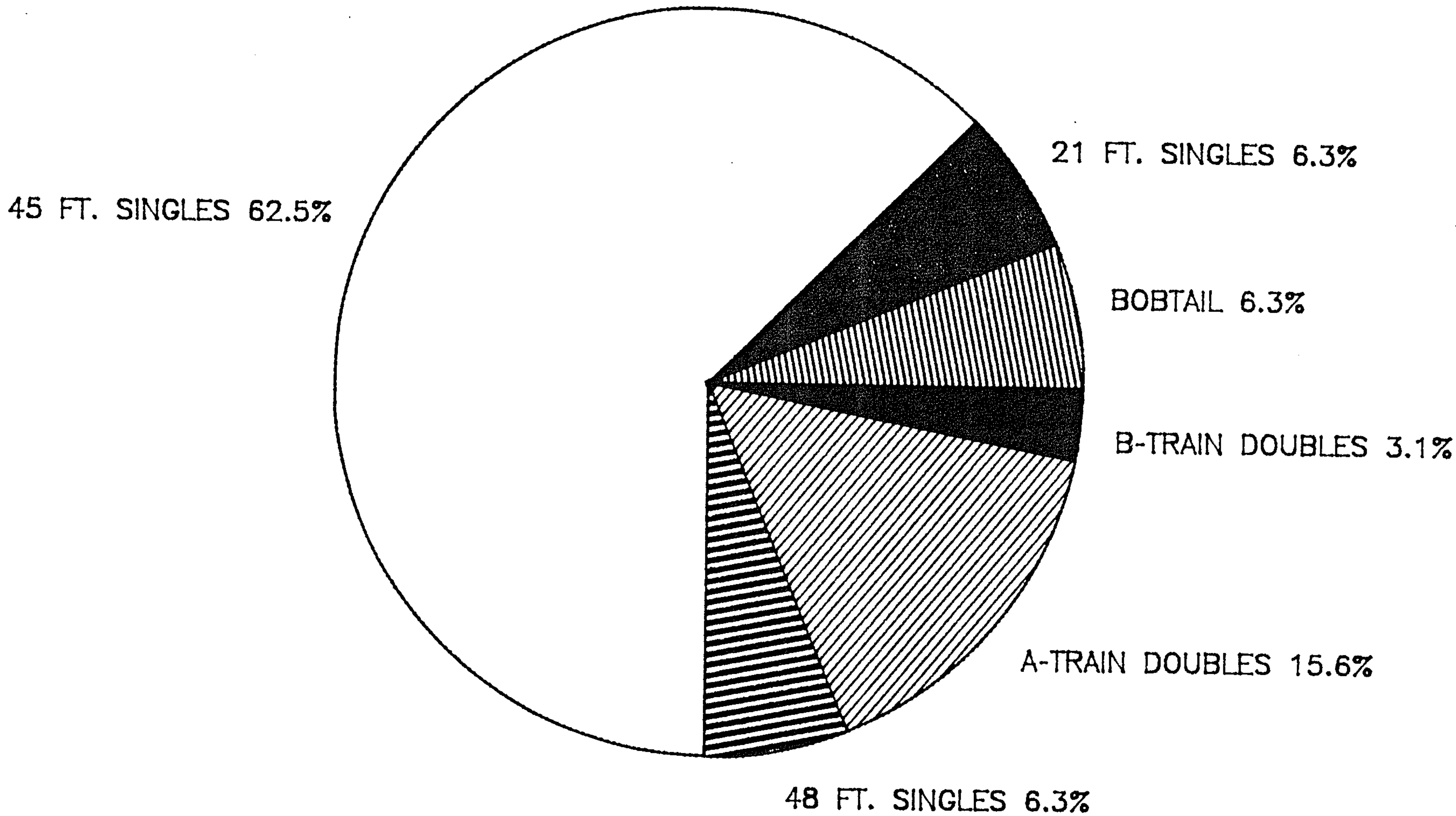


FIGURE C-3
TRAILER TYPE

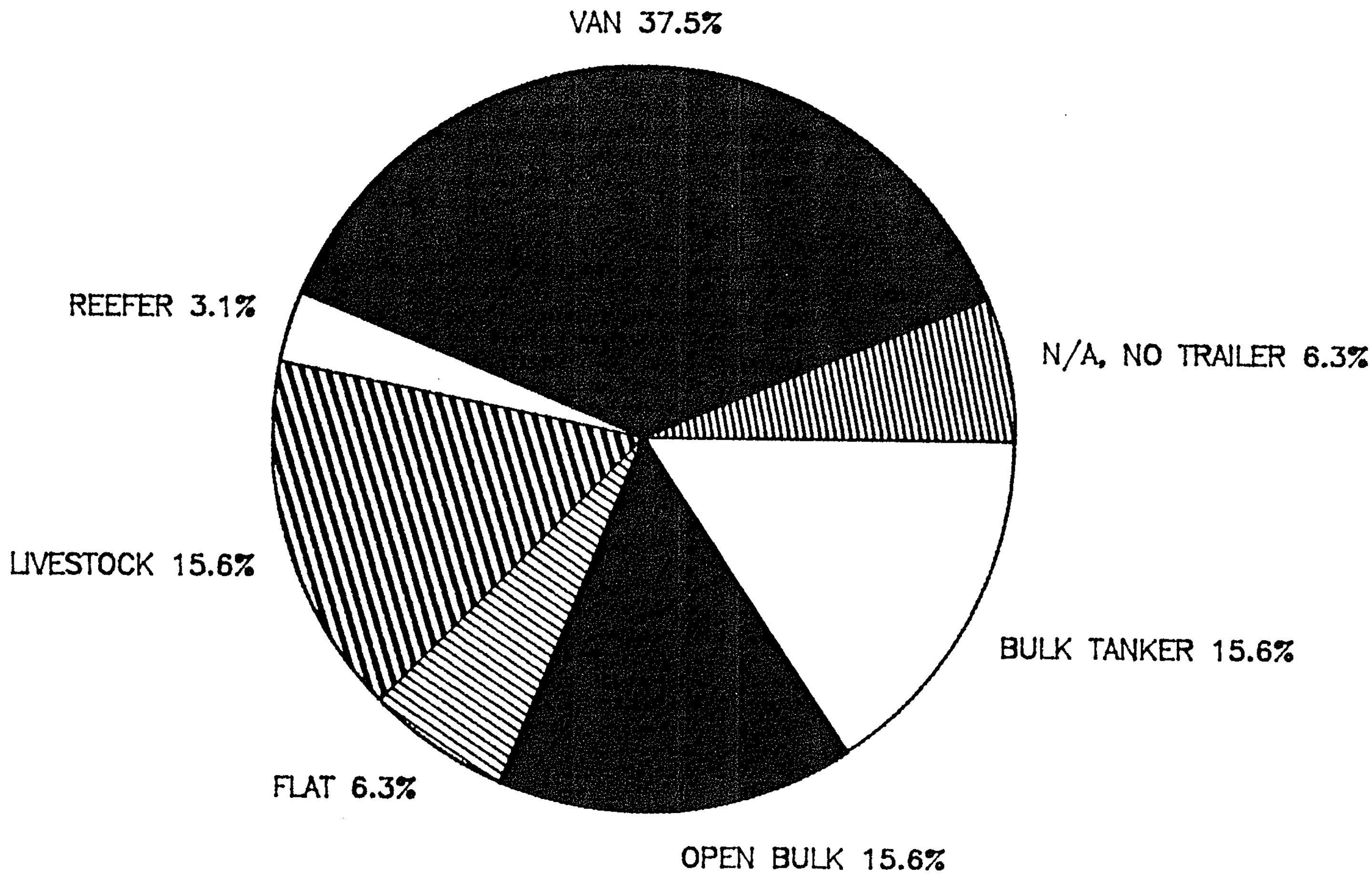


FIGURE C-4
TRAILER LOADING

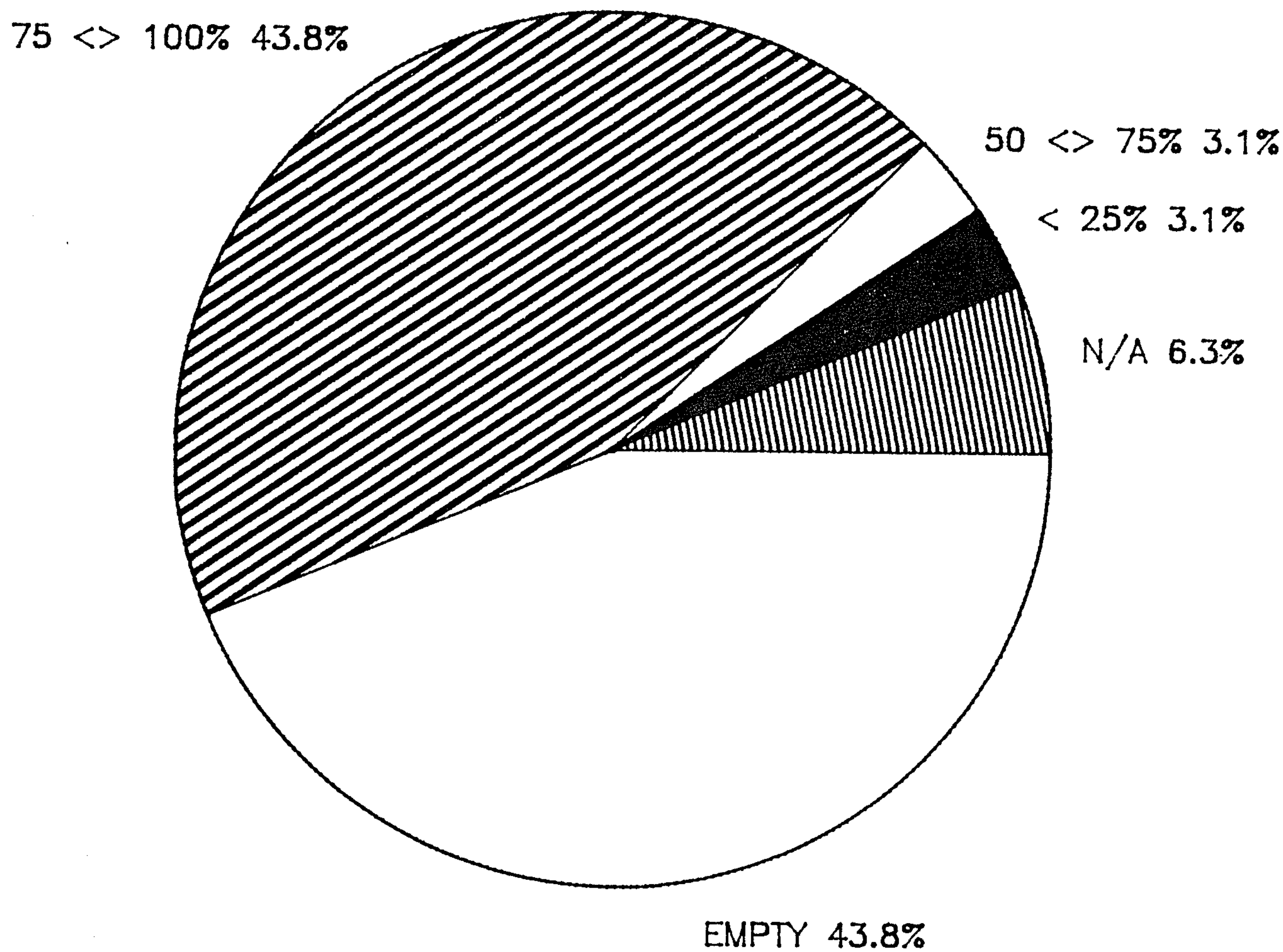


FIGURE C-5
VEHICLE SPEED

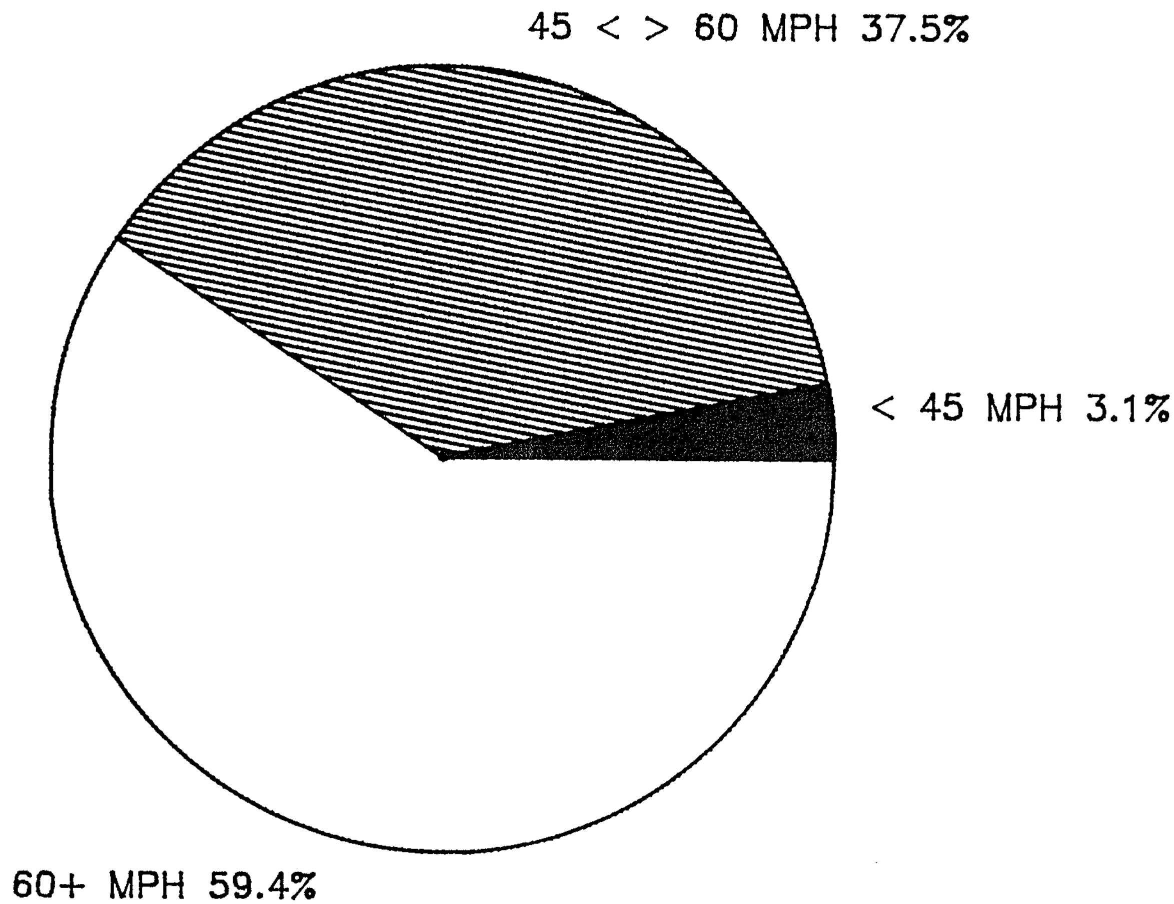


FIGURE C-6
ROAD ALIGNMENT

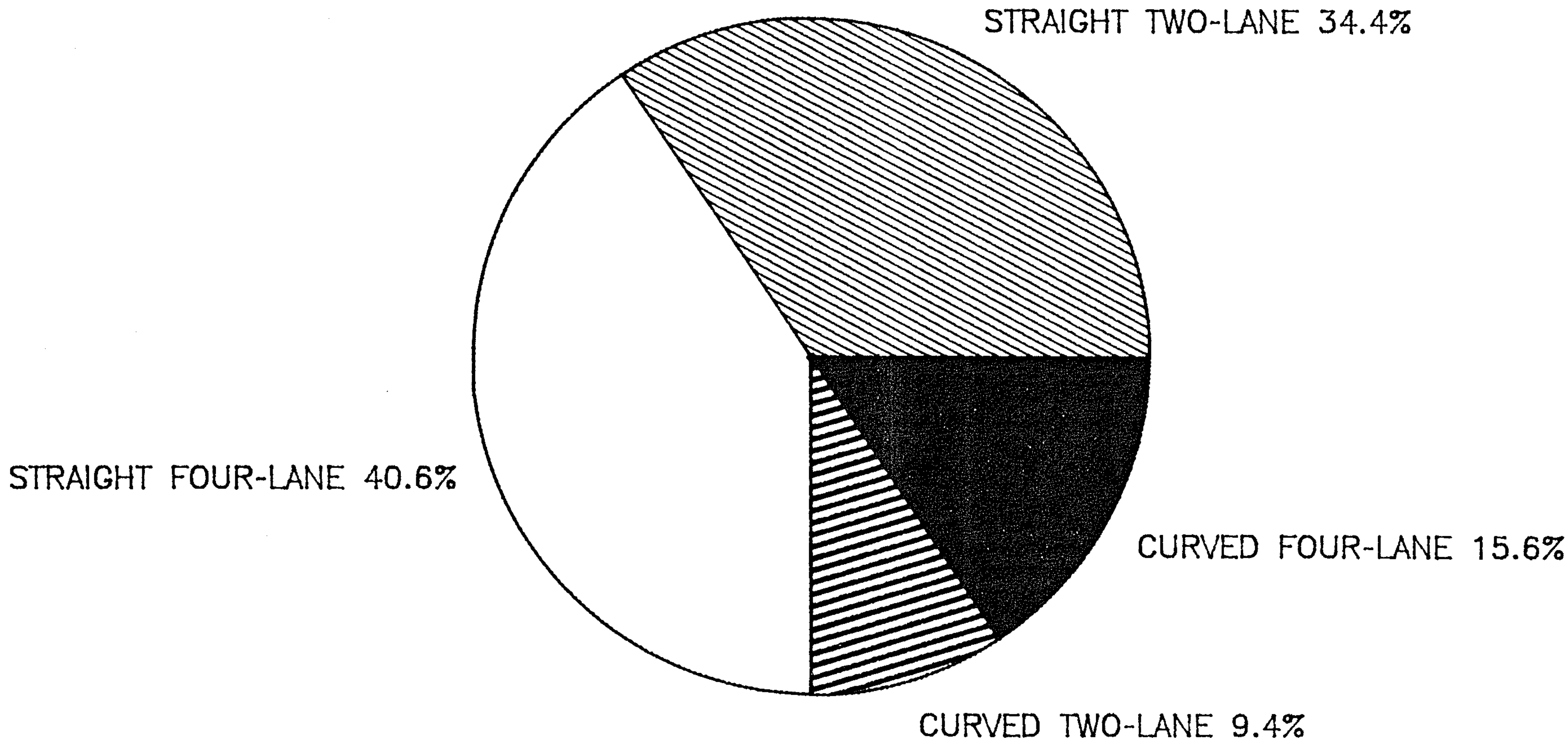


FIGURE C-7
ROAD SURFACE CONDITION

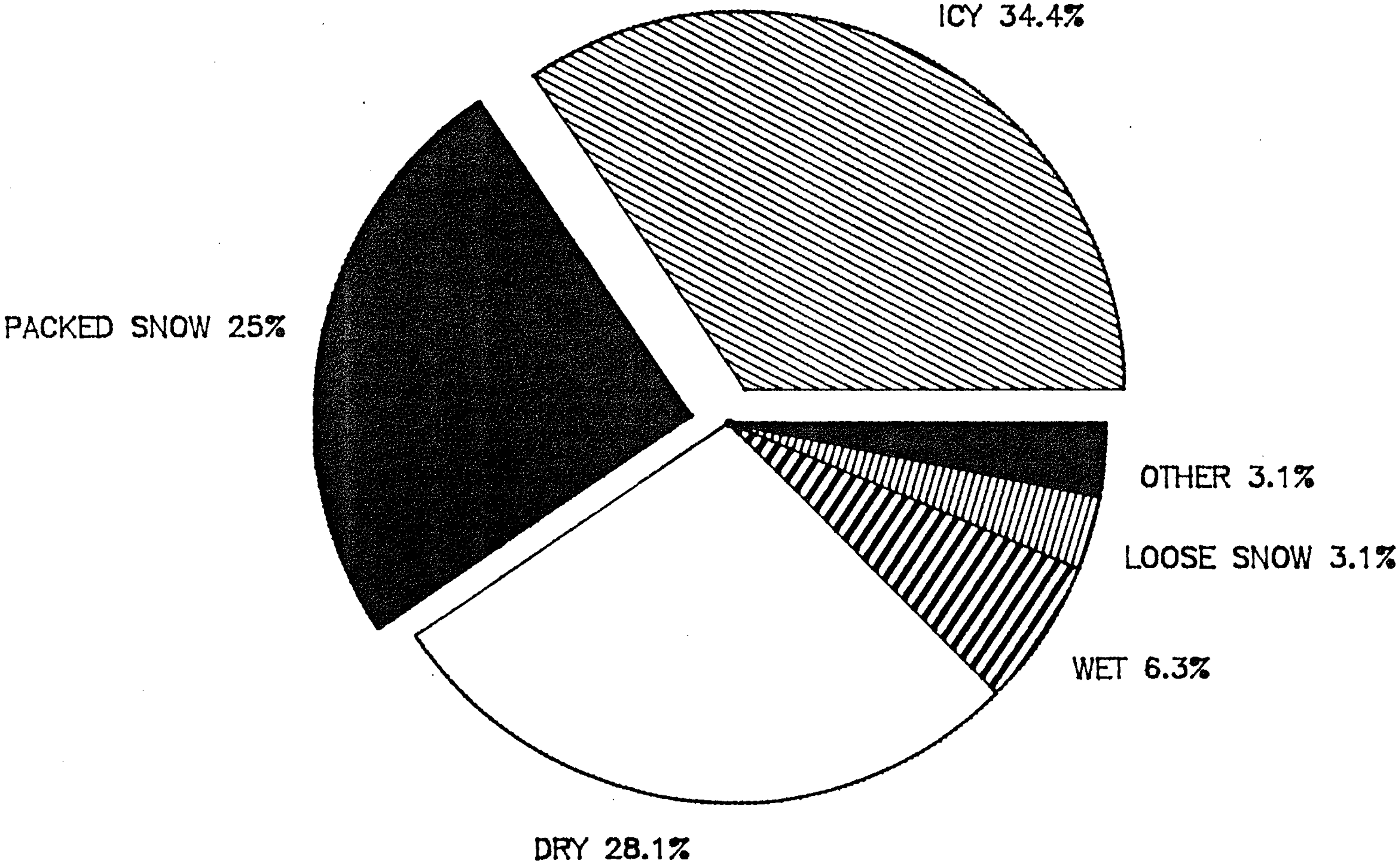


FIGURE C-8
PRECIPITATION

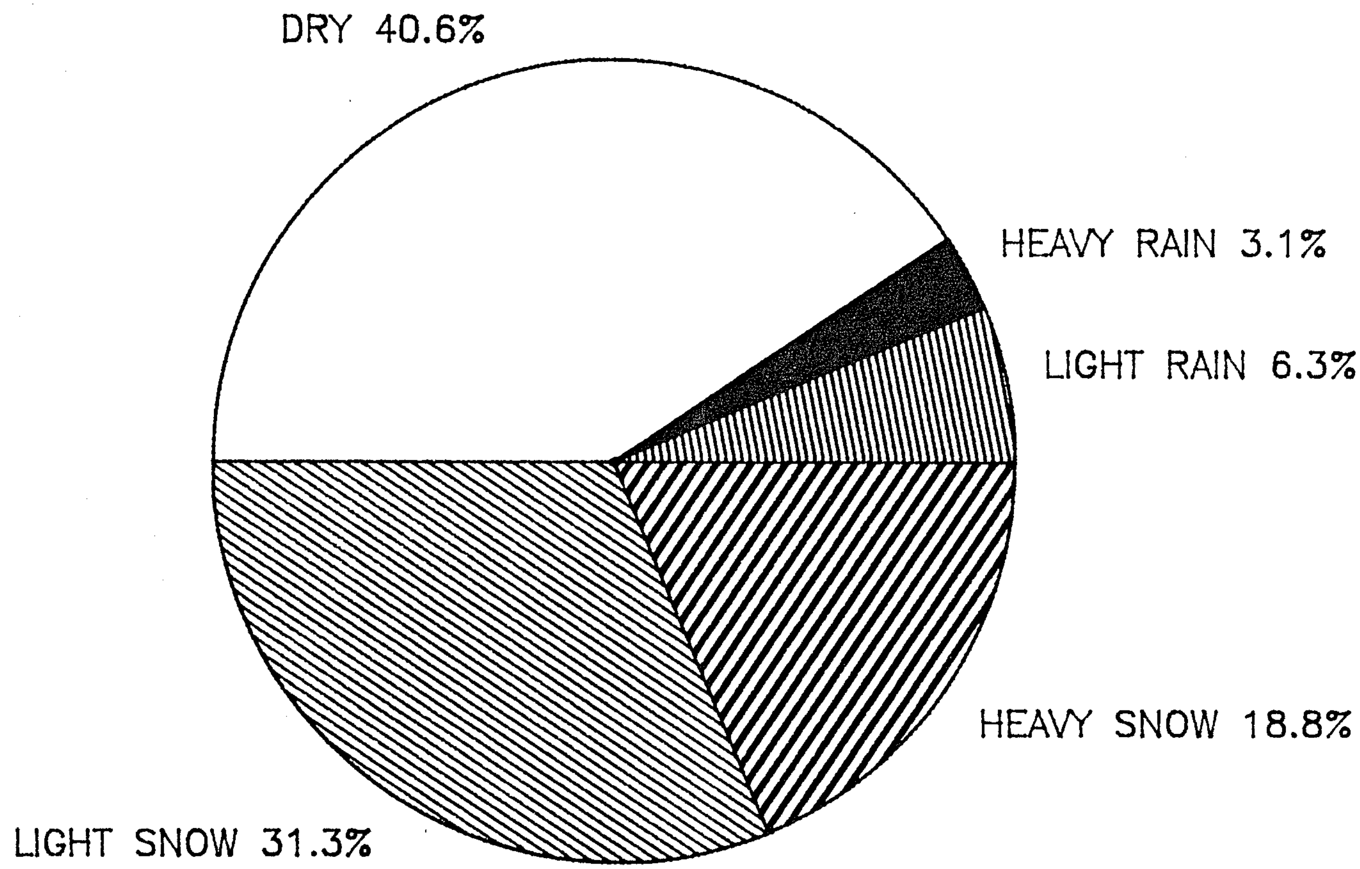


FIGURE C-9
WIND MAXIMUM VALUES

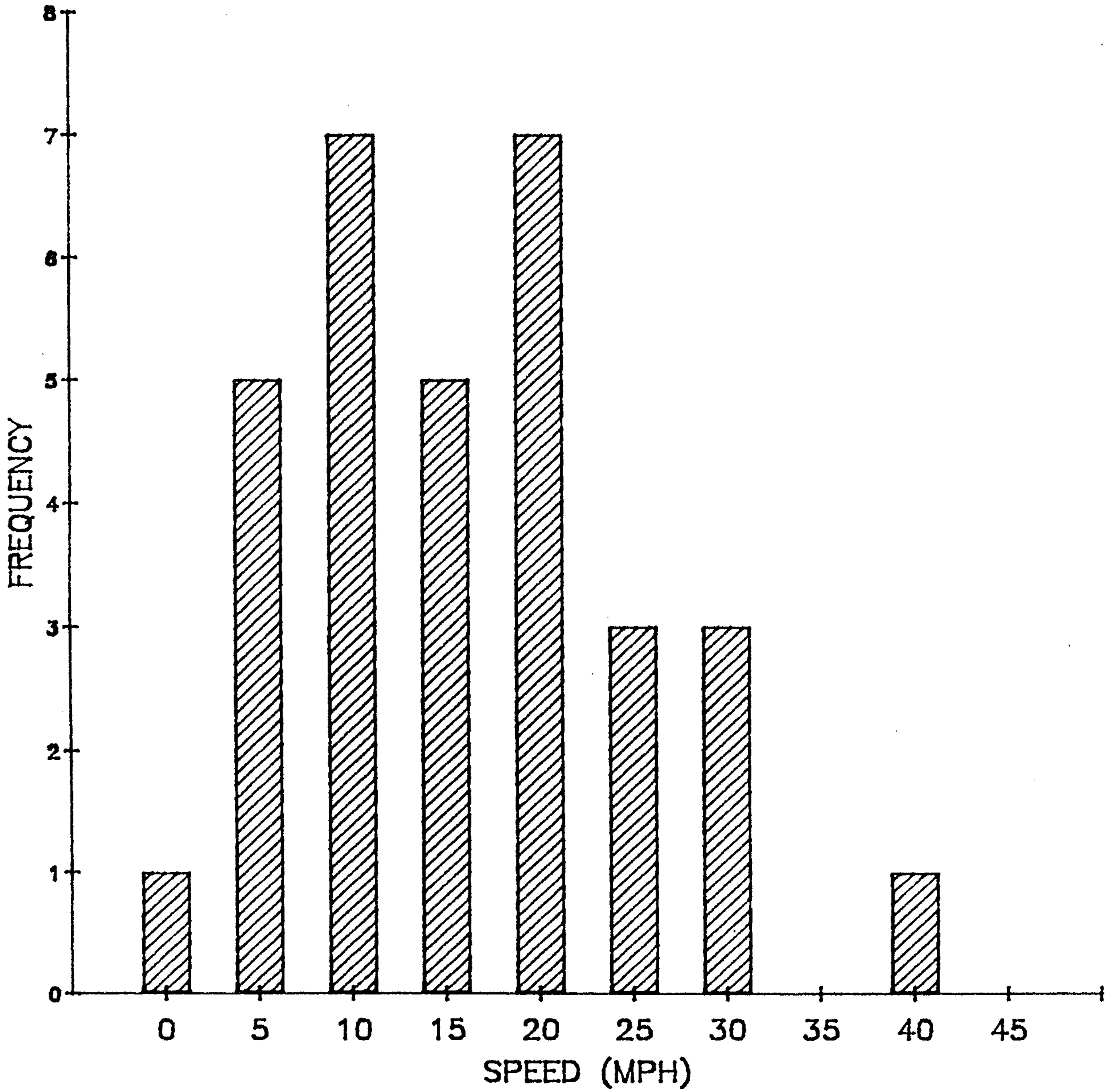


FIGURE C-10
WIND GUST VALUES

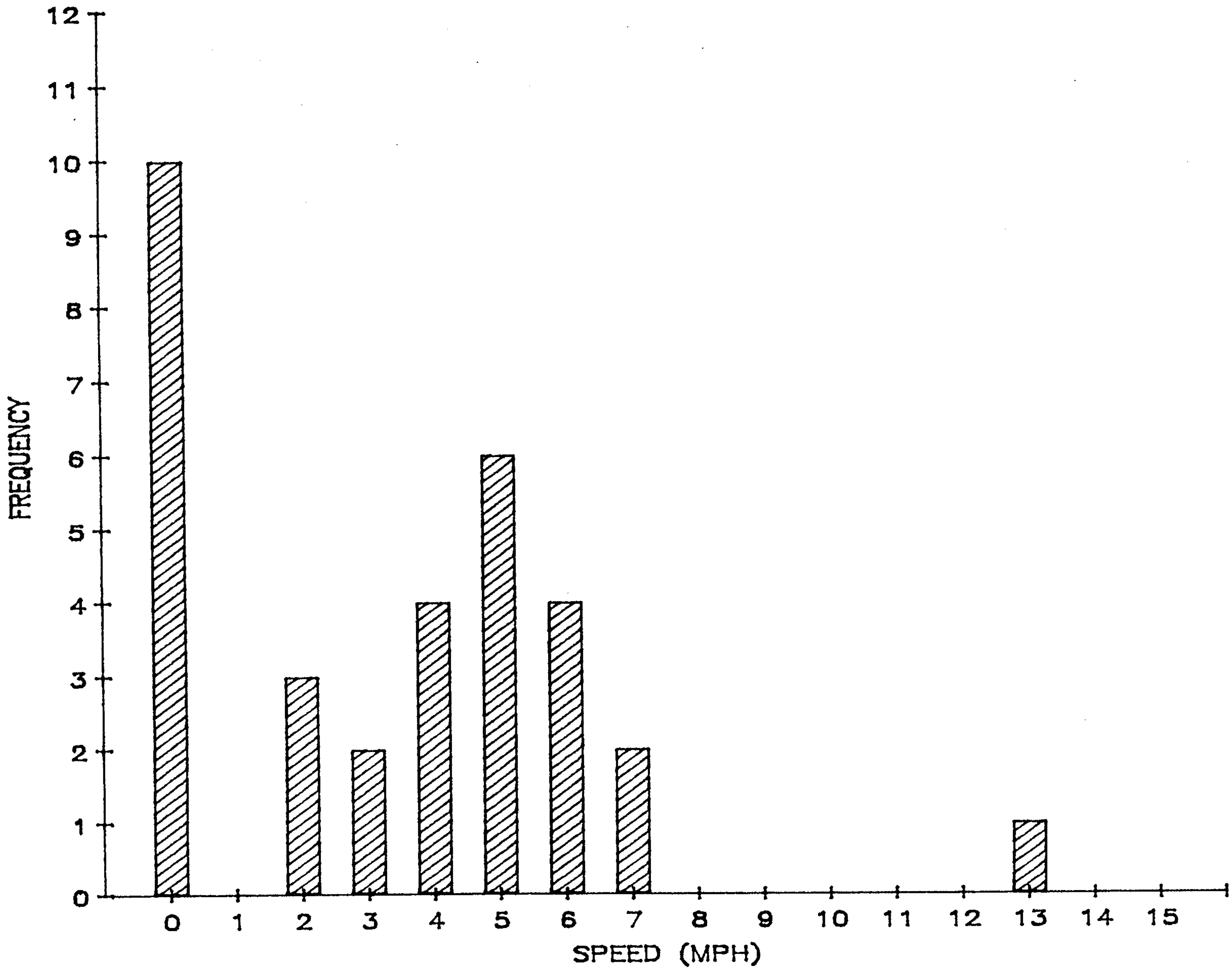


FIGURE C-11
WIND ANGLE OF INCIDENCE

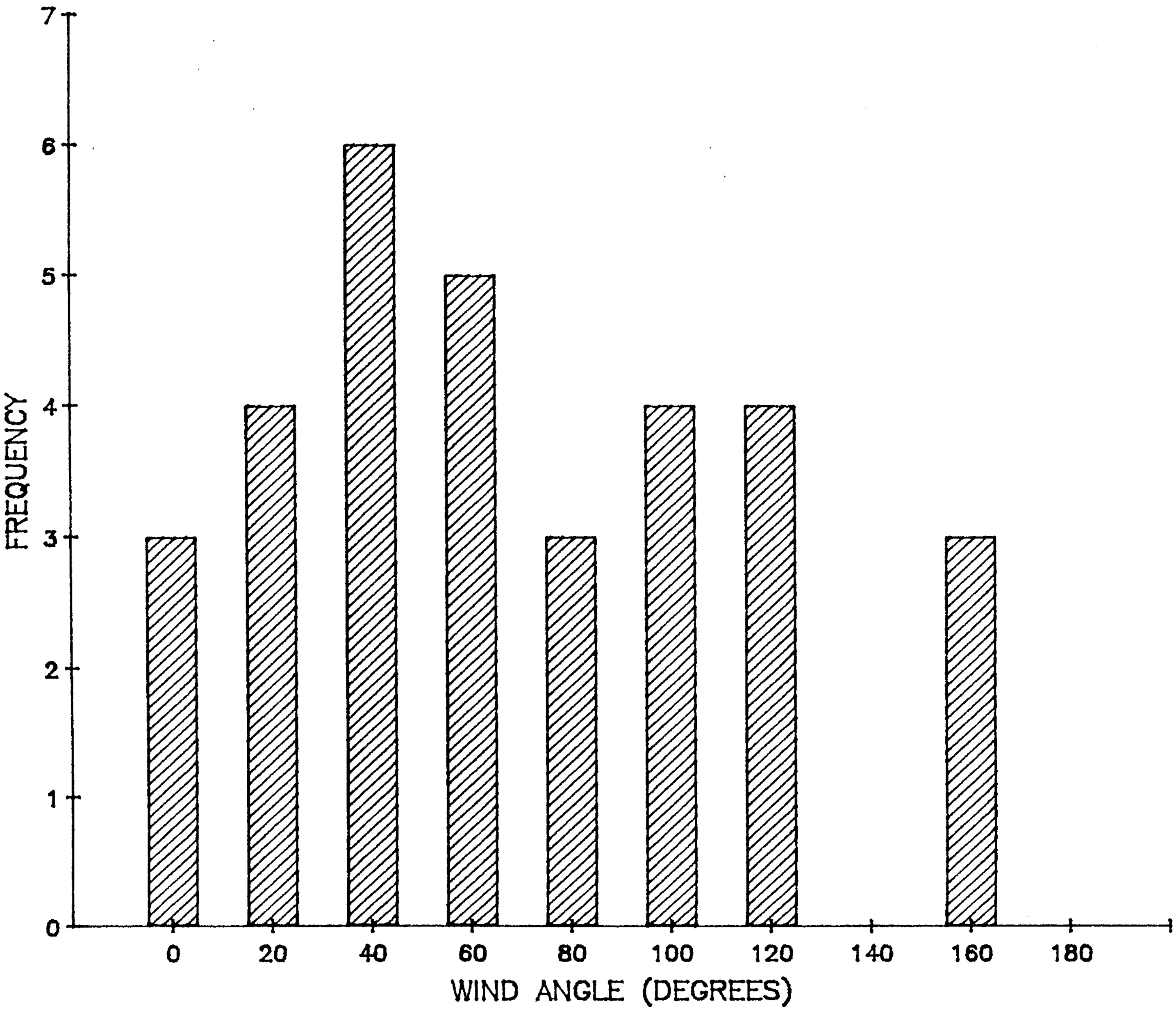


FIGURE C-12
TIME OF DAY OF OCCURRENCE

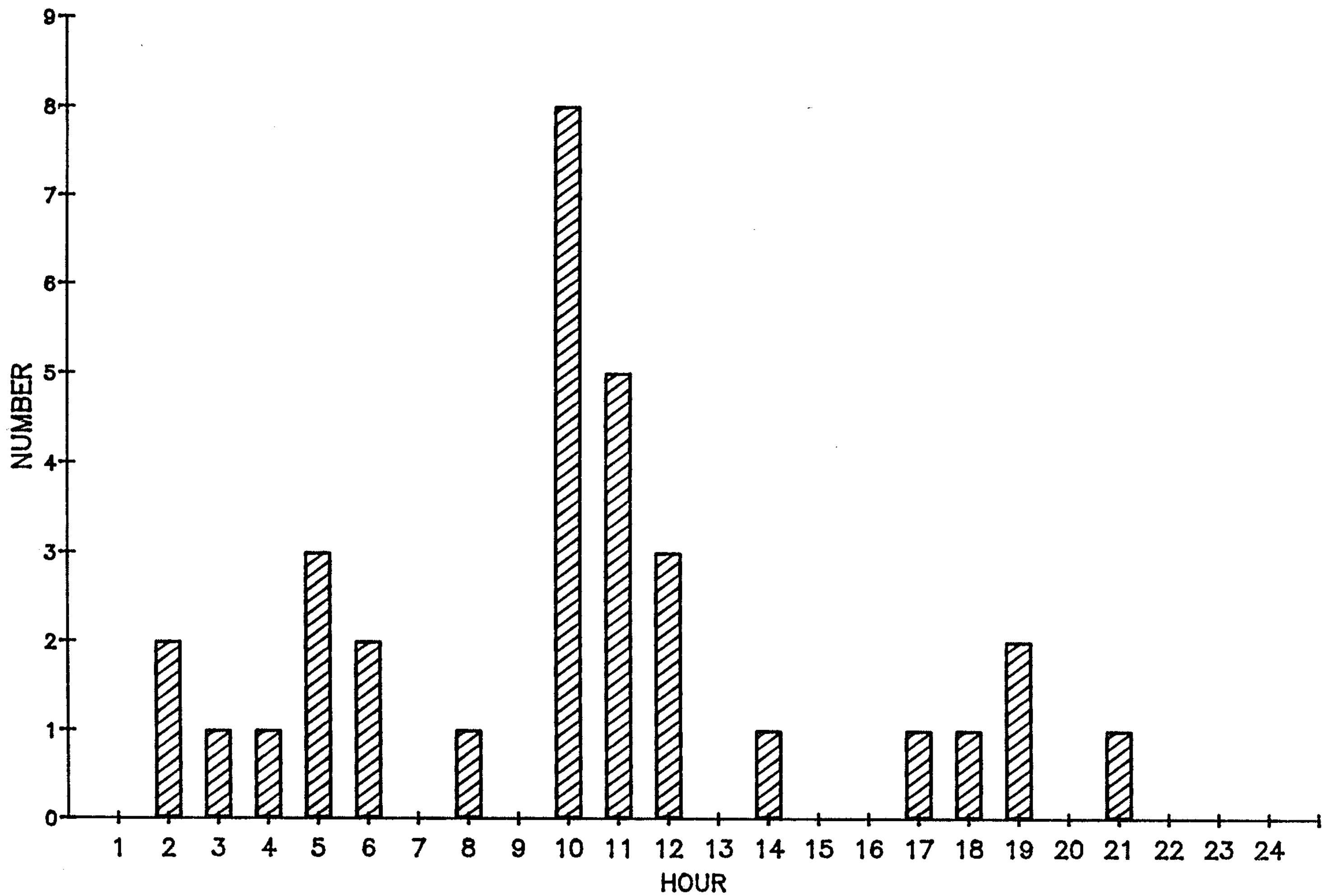


FIGURE C-13
LIGHT CONDITIONS

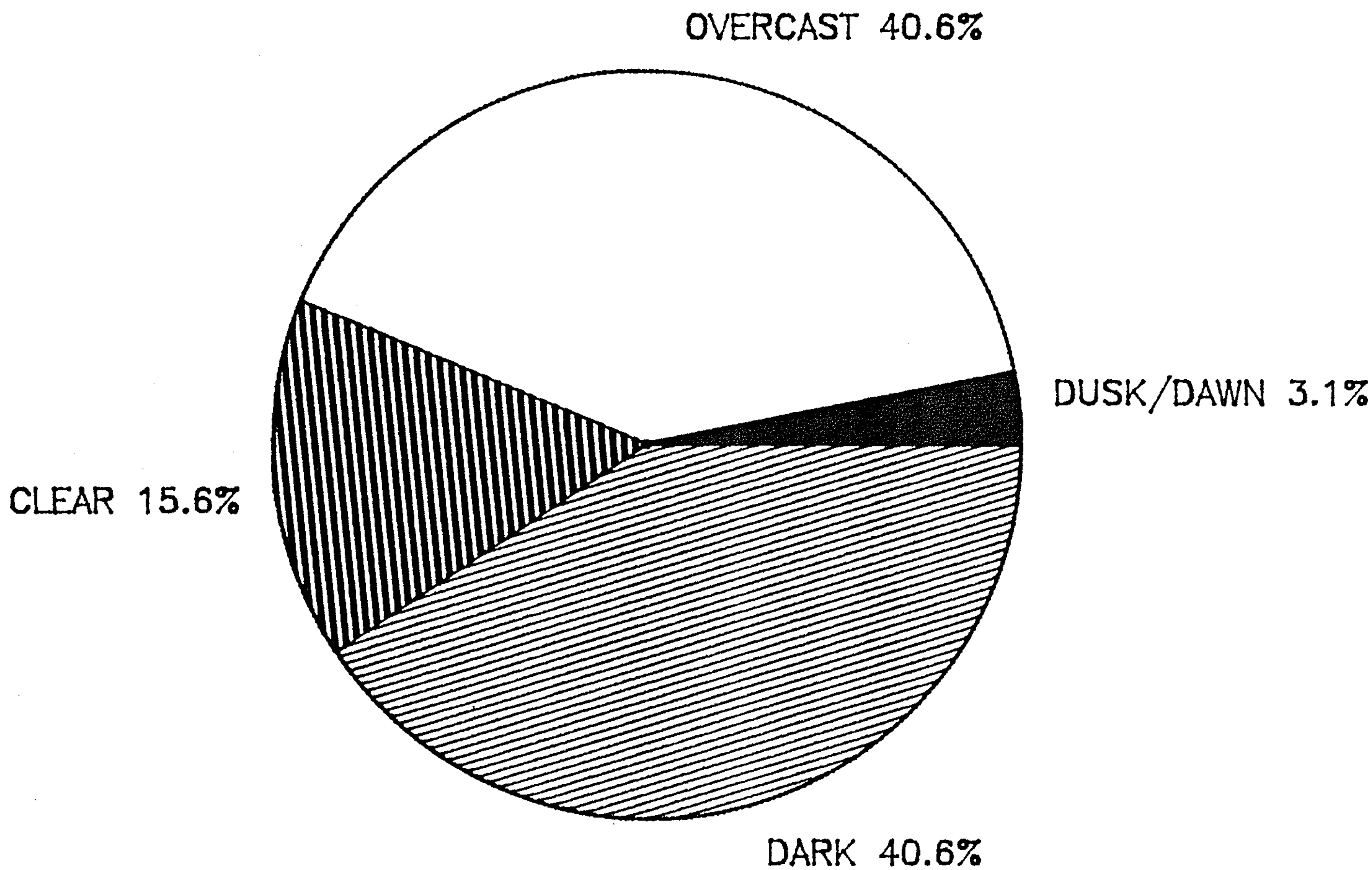
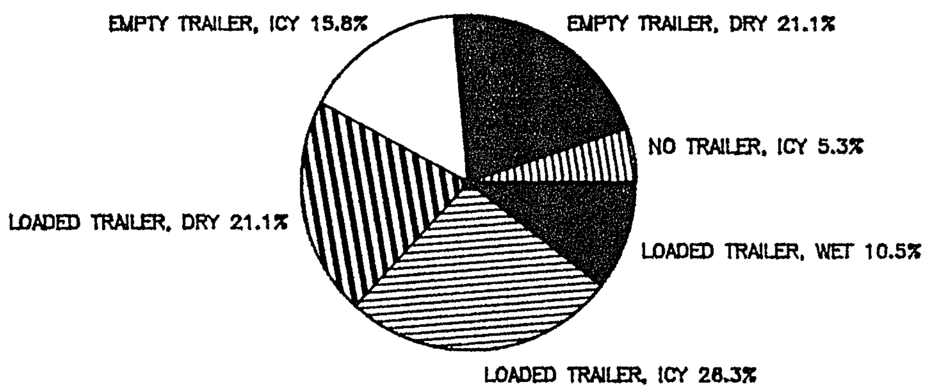
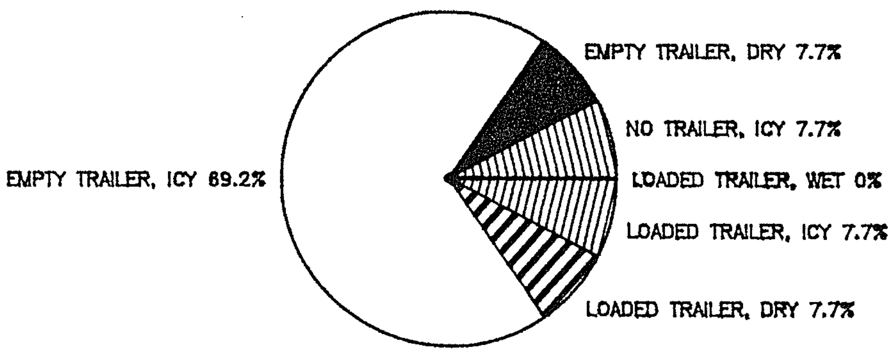


FIGURE C-14

TRAILER AND ROAD CONDITION




WIND < 15 MPH




WIND > 15 MPH

FIGURE C-15
VEHICLE OR DRIVER ACTION

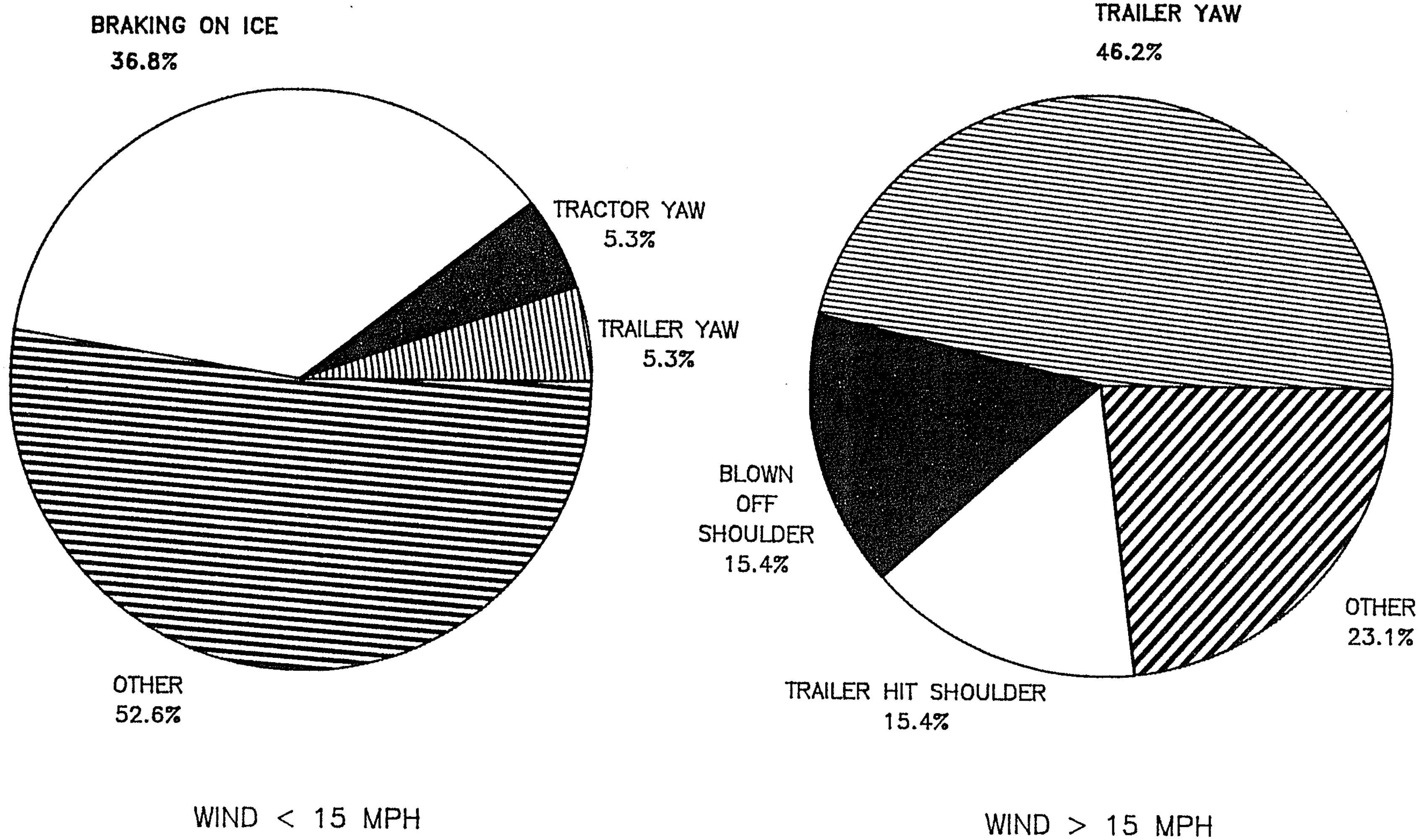


FIGURE C-16

CASE MAXIMUM WIND SPEED VS. CRITICAL WIND SPEED
EMPTY 45 AND 48 FT. TRAILERS, ROAD SPEED > 45 MPH

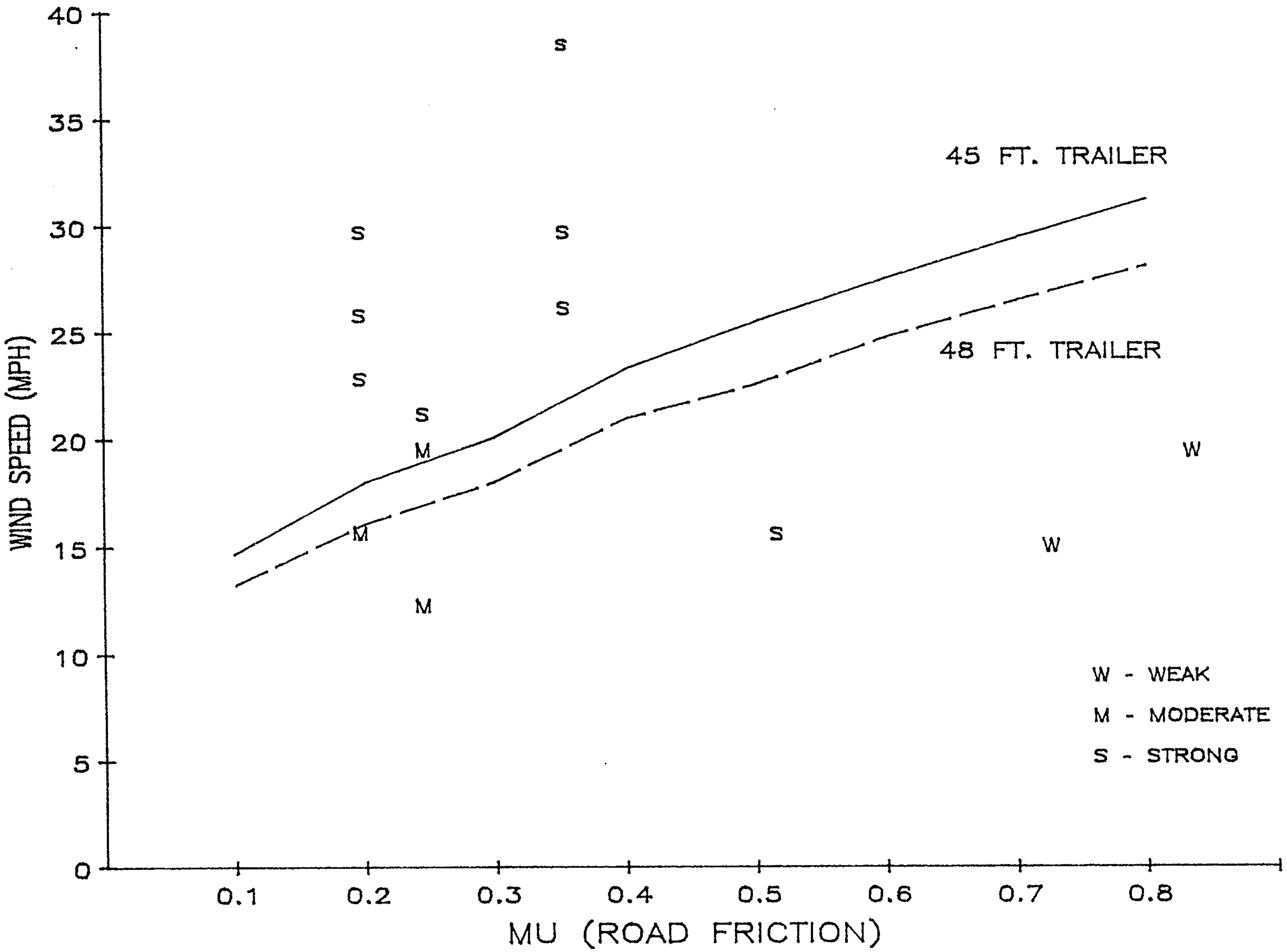


FIGURE C-17
WOLKOWICZ AND BILLING DATA
FOR JACKNIFE ACCIDENTS:
TRAILER LOADING AND ROAD SURFACE CONDITION

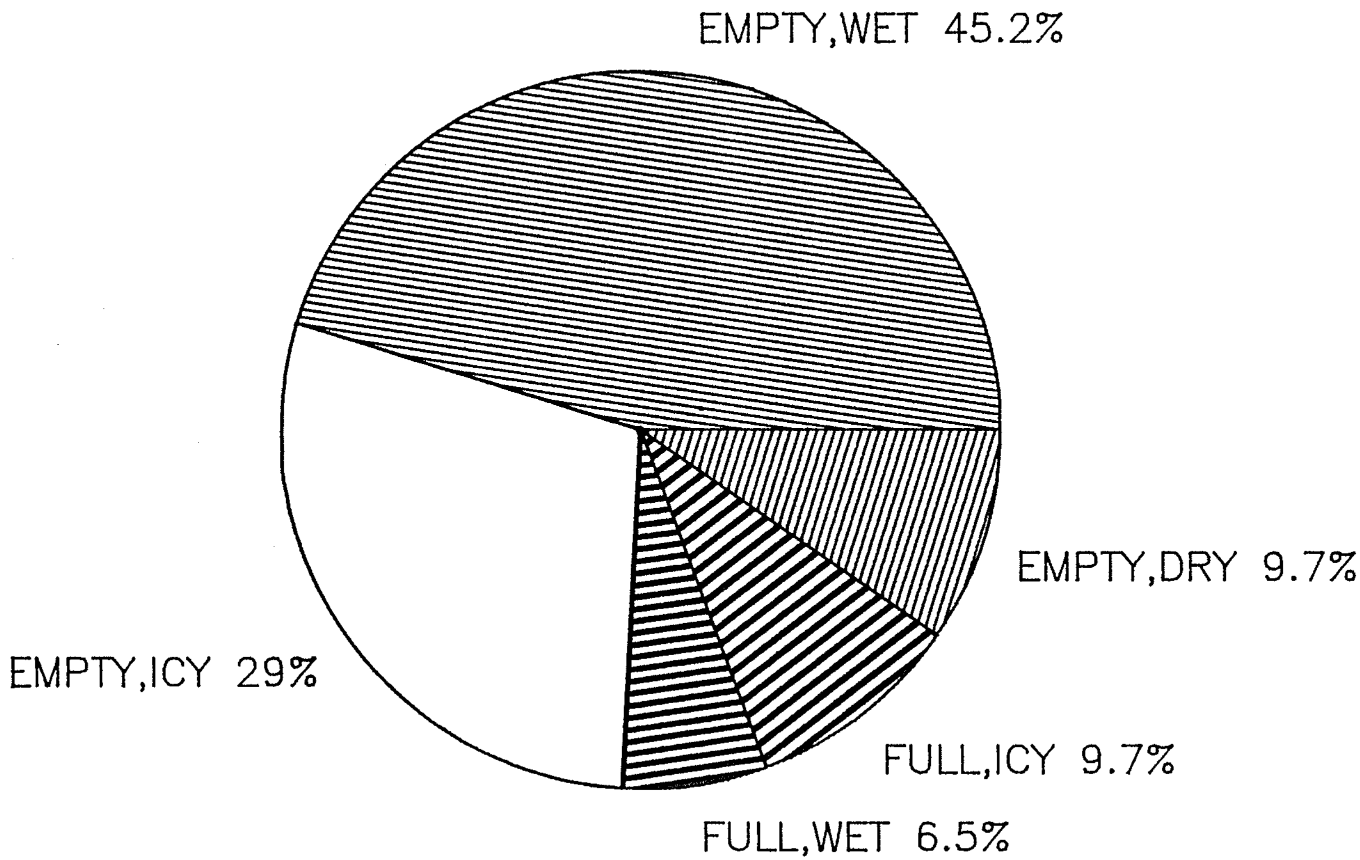


FIGURE C-18
WOLKOWICZ AND BILLING DATA
FOR ROLLOVER ACCIDENTS:
TRAILER LOADING AND ROAD SURFACE CONDITION

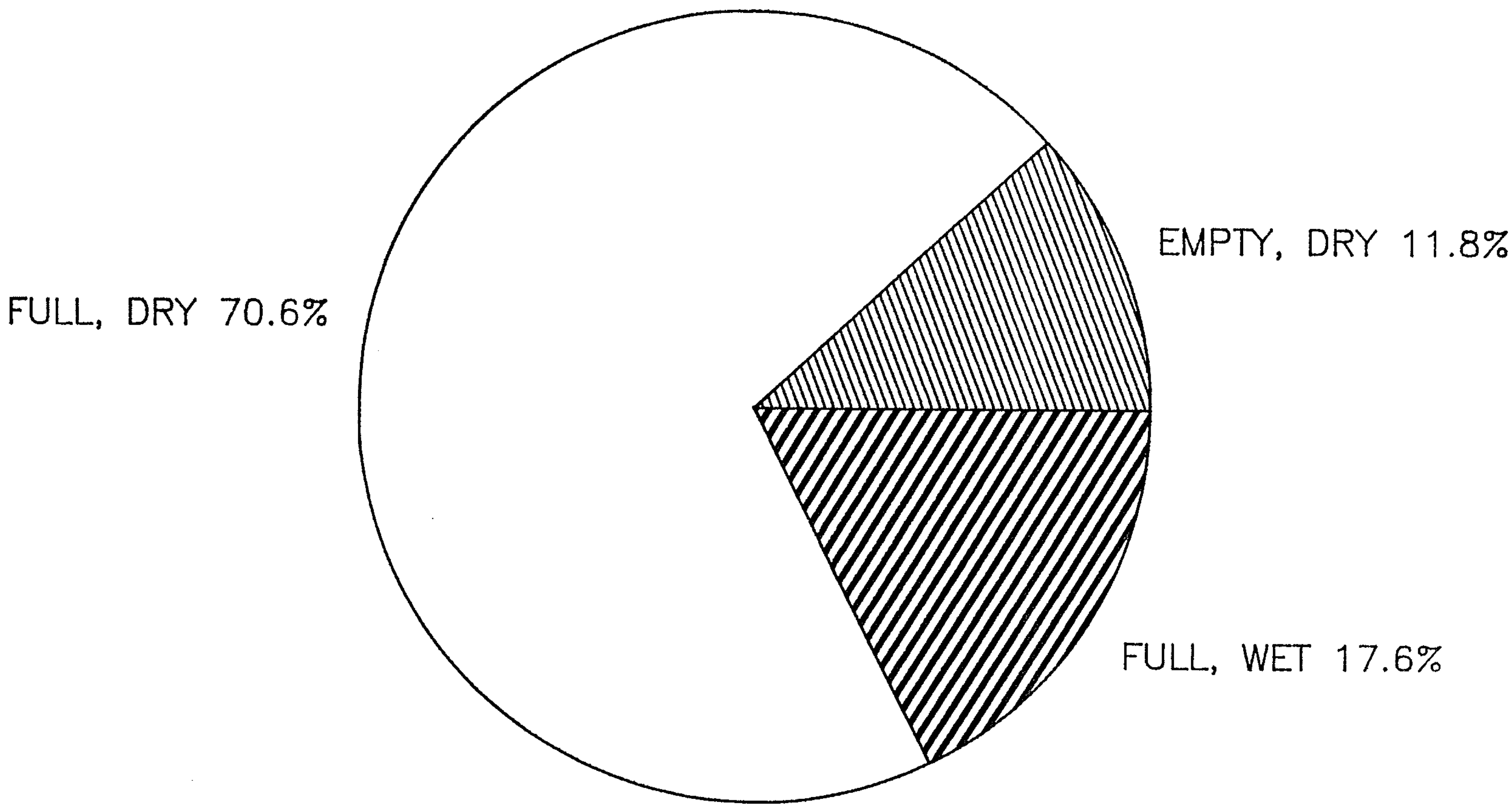


FIGURE C-19



OBLIQUE PRINCIPAL COMPONENT CLUSTER ANALYSIS

CLUSTER SUMMARY FOR 7 CLUSTERS

| CLUSTER | MEMBERS | CLUSTER VARIATION | VARIATION EXPLAINED | PROPORTION EXPLAINED | SECOND EIGENVALUE |
|---|---|---|---|---|---|
| 1 | 8 | 8.00000 | 3.56177 | 0.4452 | 0.96581 |
| 2 | 5 | 5.00000 | 4.19232 | 0.8385 | 0.49757 |
| 3 | 2 | 2.00000 | 1.51236 | 0.7562 | 0.48764 |
| 4 | 2 | 2.00000 | 1.53500 | 0.7675 | 0.46500 |
| 5 | 3 | 3.00000 | 1.45177 | 0.4839 | 0.89622 |
| 6 | 2 | 2.00000 | 1.23511 | 0.6176 | 0.76489 |
| 7 | 2 | 2.00000 | 1.18624 | 0.5931 | 0.81376 |

TOTAL VARIATION EXPLAINED = 14.6746 PROPORTION = 0.611440

| | VARIABLE | R-SQUARED WITH OWN CLUSTER | R-SQUARED WITH NEXT CLOSEST | 1-R**2 RATIO |
|---|---|---|---|---|
| CLUSTER 1 | PREC | 0.6425 | 0.0676 | 0.3835 |
| | MAXWIND | 0.5170 | 0.0847 | 0.5277 |
| | RSURENV | 0.5439 | 0.1027 | 0.5083 |
| | PCS1 | 0.2898 | 0.0401 | 0.7399 |
| | PCF1 | 0.4090 | 0.0327 | 0.6110 |
| | PCF2 | 0.5920 | 0.0570 | 0.4326 |
| | PCF3 | 0.3979 | 0.0829 | 0.6565 |
| | VSPEED | 0.1697 | 0.1173 | 0.9406 |
| CLUSTER 2 | NUMTRAIL | 0.9145 | 0.1352 | 0.0989 |
| | NUMTAX | 0.9340 | 0.0867 | 0.0722 |
| | CON | 0.8454 | 0.0334 | 0.1599 |
| | TRTYPE | 0.5828 | 0.1716 | 0.5036 |
| | TR2LEN | 0.9156 | 0.0186 | 0.0860 |
| CLUSTER 3 | COLTYPE | 0.7562 | 0.0296 | 0.2513 |
| | CSE2 | 0.7562 | 0.2065 | 0.3073 |
| CLUSTER 4 | PCS2 | 0.7675 | 0.0399 | 0.2422 |
| | PCS3 | 0.7675 | 0.1226 | 0.2650 |
| CLUSTER 5 | LIGHTCON | 0.6091 | 0.0431 | 0.4085 |
| | LOAD | 0.5632 | 0.1096 | 0.4906 |
| | TR1LEN | 0.2795 | 0.0743 | 0.7783 |
| CLUSTER 6 | CSE1 | 0.6176 | 0.0372 | 0.3972 |
| | CSE3 | 0.6176 | 0.0973 | 0.4237 |
| CLUSTER 7 | ANGLE | 0.5931 | 0.1077 | 0.4560 |
| | RALIG | 0.5931 | 0.0453 | 0.4262 |

FIGURE C–20: CLUSTERING OF HEAVY TRUCK ACCIDENT CASES
RESULTS OF SASCLUS USING MCQUITTY'S ANALYSIS

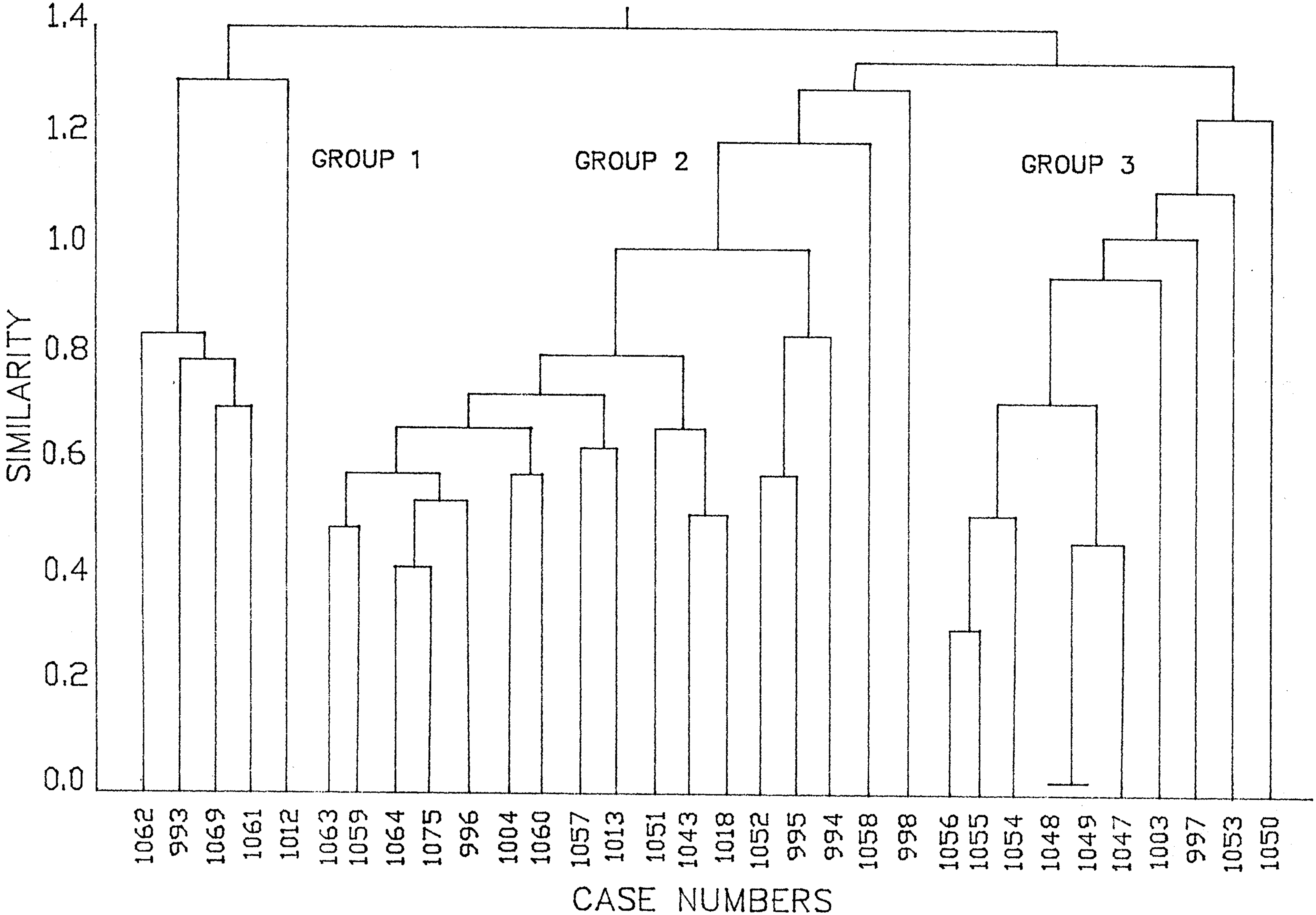


FIGURE C-21

USER SPECIFIED MECHANICAL PARAMETERS
***********************************

| | |
|---|---|
| TRAILER TYPE = | VAN |
| TRAILER LENGTH = | 48 |
| SPRING CONSTANT (LBS)= | 1,500 |
| CARGO WEIGHT(LBS)= | 10,000 |
| ROAD COEFF.= | 0.35 |
| VEH. VEL. (MPH)= | 60 |
| WIND VEL.(MPH)= | 20 |
| WIND ANGLE OF ATTACK(DEG.)= | 90 |
| GUST RANGE(MPH)= | 0 |
| AIR DENSITY (M/CU.FT.) = | 0.0024 |
| SPRING OFFSET (FT.)= | 1.5 |
| SPRUNG MASS CENTER (FT.)= | 6.5 |

TRAILER WEIGHTS
****************

| TYPE | LENGTHS | |
|---|---|---|
| **** | ******* | |
| | 45 | 48 |
| | ***** | ***** |
| VAN | 15,000 | 16,500 |
| REEFER | 17,500 | 19,500 |
| LIVESTOCK | 16,500 | 0 |

DRAG CO-EFFICIENT= 0.85

CALCULATION OF MECHANICAL PARAMETERS
***********************************

| | |
|---|---|
| AXLE WEIGHT (LBS.FORCE)= | 17,755 |
| TRAILER MASS (SLUGS)= | 505 |
| TRAILER INTERIA(M-FT.^2)= | 305,616 |
| SIDE AREA (SQ.FT.) = | 423 |

| TIME | RANDOM GUST GENERATOR (MPH) | WIND VELOCITY (MPH) | WIND SIDE FORCE (LBS.) | WIND MOMENT (FT.-LBS.) |
|---|---|---|---|---|
| ***** | *************** | ************* | ********* | *********** |
| 0 | 0 | 20 | 372 | 7,817 |
| 0.05888 | 0 | 20 | 372 | 7,817 |
| 0.11776 | 0 | 20 | 372 | 7,817 |
| 0.17664 | 0 | 20 | 372 | 7,817 |
| 0.23552 | 0 | 20 | 372 | 7,817 |
| 0.2944 | 0 | 20 | 372 | 7,817 |
| 0.35328 | 0 | 20 | 372 | 7,817 |
| 0.41216 | 0 | 20 | 372 | 7,817 |
| 0.47104 | 0 | 20 | 372 | 7,817 |
| 0.52992 | 0 | 20 | 372 | 7,817 |
| 0.8832 | 0 | 20 | 372 | 7,817 |
| 0.94208 | 0 | 20 | 372 | 7,817 |