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Fostering Development, Evaluation, and Deployment of Forward Crash Avoidance Systems (FOCAS)

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Paul S. Fancher
Zevi Bareket
James R. Sayer
Charles MacAdam
Robert D. Ervin
Mary Lynn Mefford
Jim Haugen

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16. Abstract

This work is part of a three year program to foster the development, evaluation, and deployment of forward crash avoidance systems. The work performed during the first and second years of this program has addressed adaptive cruise control and warnings based upon the motion and proximity of preceding vehicles in the path of travel. The work for this second year has emphasized features of ACC systems that could make them either more convenient and comfortable through the use of adjustable headway or safer through the use of warnings. The second year of the project presents detailed information on: driver-adjustable headway time, observations concerning drivers, neural network methods for finding driving episodes, an audio prompt for ACC intervention (crash warning), implementation of a brake-assisted lo-decel-cue, and use of an ACC test vehicle with 0.18 g deceleration authority. The findings of the first year and the work this year indicate that ACC systems with limited deceleration authority (0.05 g) can provide a level of headway control that is both useful and desired by many drivers. When controlling headway manually, drivers tend to follow preceding vehicles at closer range and to close-in more rapidly than they do when using an ACC system under similar road conditions. There are differences between the choices of headway time made by drivers from various age groups. This year's work has included the development of an audio warning based upon using range and range-rate data to compute the deceleration needed to meet a selected headway goal. Another type of warning, as well as an extension of the control authority of the ACC, was by provided by downshifting the transmission when a deceleration greater than that of coastdown was required. An additional warning system called a "lo-decel-cue" was also studied this year. This system used the foundation brakes, though only in a constrained manner, to warn the driver.

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Executive Summary

The overall goal of this program is to facilitate the development of a range of commercializeable sensors and associated application systems that supplement the forward crash avoidance performance of drivers. To aid in achieving this goal, this program seeks to develop evaluation tools, methodologies, and knowledge as needed to expedite the development of adaptive cruise control (ACC) and forward crash avoidance (FCA) systems including forward collision warning (FCW) systems.

The work performed during the first and second years of this three year program has addressed adaptive cruise control and warnings based upon the motion and proximity of preceding vehicles in the path of travel. The work for this second year has emphasized features of ACC systems that could make them either more convenient and comfortable through the use of adjustable headway or safer through the use of warnings. Future work planned for the third year will study the influences of longitudinal control employing moderate levels of braking.

The deliverable for the second year of the project is this annual report which presents detailed information on:

- driver-adjustable headway time
- observations concerning drivers (hunters, followers, and gliders)
- neural network methods for finding driving episodes
- an audio prompt for ACC intervention (crash warning),
- implementation of a brake-assisted lo-decel-cue,
- use of a borrowed ACC test vehicle with 0.18 g deceleration authority.

The findings of the first year and the work this year indicate that ACC systems with limited deceleration authority (0.05 g) can provide a level of headway control that is both useful and desired by many drivers.

When controlling headway manually, drivers tend to follow preceding vehicles at closer range and to close-in more rapidly than they do when the ACC system is in operation under similar road conditions. However, this is because the ACC system imposes a fixed minimum value for headway time. The study of adjustable headway in an ACC system indicates that, if given the capability to do so, drivers will tend to set headways that are comparable to those they use when driving manually. The experiments done in this study allowed drivers to select headway times down to a minimum of 0.7 seconds. The results of testing show that many drivers would choose this minimum, and hence we believe that some drivers would have chosen values less than 0.7 seconds if the experimental set-up would have allowed it.

There are differences between the choices of headway time made by drivers from various age groups. The younger drivers tend to like short headways, while the older drivers are not inclined to choose headways less than 1.4 seconds. The evidence supports the conclusion that an adjustable headway feature is needed so that different drivers can personally select a headway time that they feel is compatible with the existing road and traffic conditions.

With regard to setting minimum and maximum headway times to constrain the range of headways for ACC systems, data for 36 subjects driving manually on freeways were analyzed to determine driving style with respect to average range-rate (relative velocity) and to the most likely value of the headway time chosen by the driver. Those that chose to travel at relatively high levels of closing velocity and small headway times were named "hunters"; and those that chose to travel more slowly than the surrounding vehicles and at relatively large headway times were called "gliders." The drivers whose choices fell in between these two groups were called "followers" because they tended to travel at speeds and range distances that put them in the neighborhood of the general flow of the traffic stream.

A range of headway times from 1.0 to 2.0 seconds was found to be approximately typical of those drivers that are content to go with the flow of surrounding traffic. The fixed ACC system used in the first year had a headway time setting of 1.4 seconds which is very close to the middle of the follower characteristics. Our more recent analysis of results covering hunters, gliders, and followers reconfirms the original choice of 1.4 seconds as a headway time setting that many drivers will find acceptable. Nevertheless, hunters (who are mainly younger drivers) will tend to feel that 1.4 seconds is too long for dense traffic conditions and gliders (who are mainly middle aged and older drivers) will generally prefer longer headway times. The range of headway time adjustment from 1 to 2 seconds represents a compromise that appears to be satisfactory to a wide range of drivers. The current field operational testing of ACC is using this range.

Selection of the allowable range of headway time is a design issue for future ACC systems. On the one hand, it seems logical that longer headway distances enhance the margin for safety, given the delay in typical driver reaction to abrupt conflicts in headway. On the other hand, our data indicate that many drivers do not seek such margins when they are driving. Thus, there is a tension between the desire to please the customer by accommodating short headway and concern for the associated safety hazards. A minimum value of 1.0 second for ACC headway time, for example, may well provide a safety benefit because it would provide a greater headway safety margin than that used by many drivers driving manually. And, of course, neither manual driving nor ACC could be expected to handle the worst-case driving scenarios.

An evolutionary approach would mean that ACC is a step towards an emergency automatic crash avoidance system but that will not be the primary capability of first-coming ACC products. ACC should, nevertheless, tend to reduce the level of exposure to potentially risky, close-following situations.

With regard to analyzing data from ACC operation, there are needs to look at individual incidents and situations as well as the broader statistical and frequency or probability implications of the data. Although various scenarios related to ACC operation seem relatively easy to conceptualize and define precisely, it is by no means as easy to find examples of these scenarios in the data. During the first year, rule-based definitions of driving scenarios were employed with only limited success at finding so-called "streams" of data (time segments capturing a stereotypical form of conflict). Example scenarios included following at constant speed, sudden merges into the path of the ACC vehicle, sudden slowdown by the preceding vehicle, closing in from long range, etc. In order to aid in automating the capture process for large sets of data, a neural network approach was developed and tried. Example results have been successfully produced. They show that the approach has promise, but is still in the research phase. Results to date show that the neural net identifies scenarios correctly in approximately 80 or 90 percent of the cases. Even at its present state of development the neural net approach can be used as a quick way to find samples of particular driving scenarios. It is not clear, however, whether the accuracy of identification would be adequate for directly counting different types of conflicts or driving scenarios in order to express the frequency/probability of their occurrence.

This year's work has also included the development of an audio warning based upon using range and range-rate data to compute the deceleration needed to meet a selected headway goal. As an example, the warning system could use a headway distance of 0.5 times the desired headway employed in the controller and a deceleration level of 0.05 g to establish a warning boundary. By such an arrangement the driver would be prompted to intervene whenever the pending headway conflict is computed to be more severe than can be managed by the ACC system. Clearly the values chosen for the warning criteria depend upon the characteristics of the particular ACC system. Nevertheless, the concept of using a deceleration parabola as the warning boundary, as demonstrated this year, is believed to have fundamental merit.

Another type of warning, as well as an extension of the control authority of the ACC, was provided by downshifting the transmission when a deceleration greater than that of coastdown was required. In this case a constant deceleration parabola was also used as a boundary. When the measured range falls below this parabola, the transmission will downshift. The additional deceleration provided by the downshift not only slows the vehicle more rapidly but it also provides a deceleration cue to the driver. The choice of parameters in deceleration parabolas for the audio warning and the downshift function can be chosen to ensure that downshift precedes audio warning. In this manner the driver receives a two-stage cue indicating the need for additional deceleration.

An additional warning system called a "lo-decel-cue" was also studied this year. This system used the foundation brakes, though only in a constrained manner, to warn the driver. The idea is to apply a limited level of brake pedal actuation corresponding to approximately 0.1 g of deceleration, for example. This braking is applied for a short period of time and also causes the ACC controller to disengage. In response to this type of cue, the driver must resume manual control of the vehicle deciding whether to later re-engage the ACC or to continue driving manually. The brake-induced cue is seen as a third and final stage of warning and thus comes after downshift and audio warnings have occurred.

Limited experience operating an ACC system having approximately 0.18 g of controlled braking capability was also obtained during year two. Preliminary evaluation of this system indicates that the additional control authority due to braking adds to the comfort and convenience of ACC especially when operating in fairly dense traffic that approaches the capacity of the freeway.

The second year effort has added understanding and improved methods for studying higher-level functionalities in the third year. Major issues remain in transitioning from ACC as a comfort and convenience system to systems that provide a certain level of crash warning and even crash avoidance capability for reacting to hazards that develop in the forward view. The closing sections of the report present concepts and ideas concerning how the use of the foundation brakes are to be used in controlling headway. These sections indicate that a goal-oriented control strategy will be used in a manner that has the same overall headway control concept and the same internal control loop for throttle control as has been employed in the first and second years, but with an additional internal control loop for brake control. The rationale for using a braking control authority of less than 0.2 g in this internal loop is developed in the closing sections of this report.

1.0 Introduction

The overall goal of this program is to facilitate the development of a range of commercializeable sensors and associated applications systems that supplement the forward crash avoidance performance of drivers. To aid in achieving this goal, this program seeks to develop evaluation tools, methodologies, and knowledge as needed to expedite the development of adaptive cruise control (ACC) and forward crash avoidance (FCA) systems including forward collision warning (FCW) systems.

This report pertains to work done during the second year of a three year effort. The annual report for the first year (see reference [1]) provides detailed information on (1) the characteristics of a baseline ACC system, (2) the performance of the baseline system, and (3) the human factors and engineering aspects of problematic situations related to ACC driving. Although this second annual report is a "stand alone" document, there is a wealth of pertinent background information in the first annual report.

(Please note that the meanings of the terms "adaptive cruise control (ACC)," "intelligent cruise control (ICC)," and "autonomous intelligent cruise control (AICC)" are essentially equivalent in the context of this report. However, driver/participants in the study are often mislead or distracted and may develop misconceptions when the term "intelligent" is used. The acronym "ACC" is used throughout the remainder of this document.)

The deliverable for the second year of the project is this annual report. The report includes (1) test results and systems-development experience for more complex ACC features including driver-adjusted headway and (2) methodology and findings pertaining to a low-decel-cue warning supplement. A final report for the entire FOCAS project is to be completed at the end of the third year. In addition to the work covered in the first two years, the final report will provide results and findings pertaining to the use of moderate levels of braking for adaptive cruise control and crash prevention purposes.

Specifically, this second annual report presents detailed information on:

- driver-adjustable headway time
- observations concerning drivers (hunters, followers, and gliders)
- neural net methods for finding driving episodes
- an audio prompt for ACC intervention (crash warning),
- implementation of a brake-assisted lo-decel-cue,
- use of a borrowed ACC test vehicle with 0.18 g deceleration authority.

The report concludes with sections relating this year's findings on ACC to crash avoidance concepts.

2.0 Adjustable Headway Study (driver-adjustable headway time)

2.1 Participants

A total of twelve licensed drivers participated in the study. Four participants came from each of the following age groups: 22-30, 41-52, 69-74. The three age groups were balanced for gender and experience using conventional cruise control. All participants in the adjustable headway study were selected at random from participants in the first FOCAS study (see reference [1]). Each participant in the adjustable headway study had previously driven the same vehicle under ACC for a period of approximately one hour. The only new feature of the vehicle was the driver's ability to adjust headway time. Previously the participants had experienced only a fixed headway setting of 1.4 seconds. A Saab 9000 was used as the test vehicle for all drivers.

2.2 Method

Each participant was accompanied by a research assistant who instructed the participant to drive a 43-mile route (86 miles round trip) on highways and expressways from Ann Arbor to Royal Oak, Michigan (M-14, I-275, and I-696) on weekday mornings between the hours of 9 and 11 am. Two methods were employed in assessing preferred headway selections; a modified version of the method of adjustment and free adjustment. The order in which these methods were experienced by participants was balanced. For both conditions the range of headway adjustment was 0.7 - 2.5 seconds. No information was displayed to participants regarding their selection of headway. Participants were required to make adjustments in headway using only information that was available by looking forward through the windshield (the distance between a proceeding vehicle and the research vehicle). Adjustments in headway were achieved by the participants pressing one of two buttons located on the console. These buttons were labeled "closer" and "farther." A single depression of the "closer" button would decrease the headway setting by 0.1 seconds. Pressing the "farther" button would increase the headway setting by 0.1 seconds. Participants were encouraged to experiment with a wide range of headway times, but were instructed to make discreet changes in headway (single button presses). After each adjustment participants were instructed to allow a short period of time such that the vehicle could respond to the change in headway selection. At no time were the participants informed of the absolute value of the headway setting, or whether they had reached the maximum or minimum range of headway settings.

In the method of free adjustment participants were allowed to adjust the headway at will from an initial setting of 1.4 seconds. However, in the modified method of adjustment participants always began at the maximum headway setting of 2.5 seconds and were only allowed to shorten the headway (minimum headway of 0.7 seconds). In the modified method of adjustment participants were instructed to adjust the headway down from the starting value (2.5 seconds) until they reached a "comfortable" following distance. The procedure for the modified method of adjustment was repeated as many times as possible over the 43-mile route.

2.3 Results

In the method of free adjustment condition, approximately 90 percent of the time spent following another vehicle (i.e., the presence of another vehicle was detected by the ACC system) was at a headway time of 0.7 to 1.7 seconds. Approximately 50 percent of the following was performed at a headway time of 0.7 to 1.2 seconds. Considerable difference in the distributions of selected headway was observed between age groups in the method of free adjustment condition (see Figures 2.1 - 2.3). Specifically, the youngest participant group had a distribution of selected headway times with the lowest median value (1.1 seconds compared to 1.3 and 1.5 seconds for the middle-aged and older participant groups, respectively). However, a floor effect resulting from the fixed minimum headway of 0.7 seconds was observed for both the young and middle-aged participant groups.

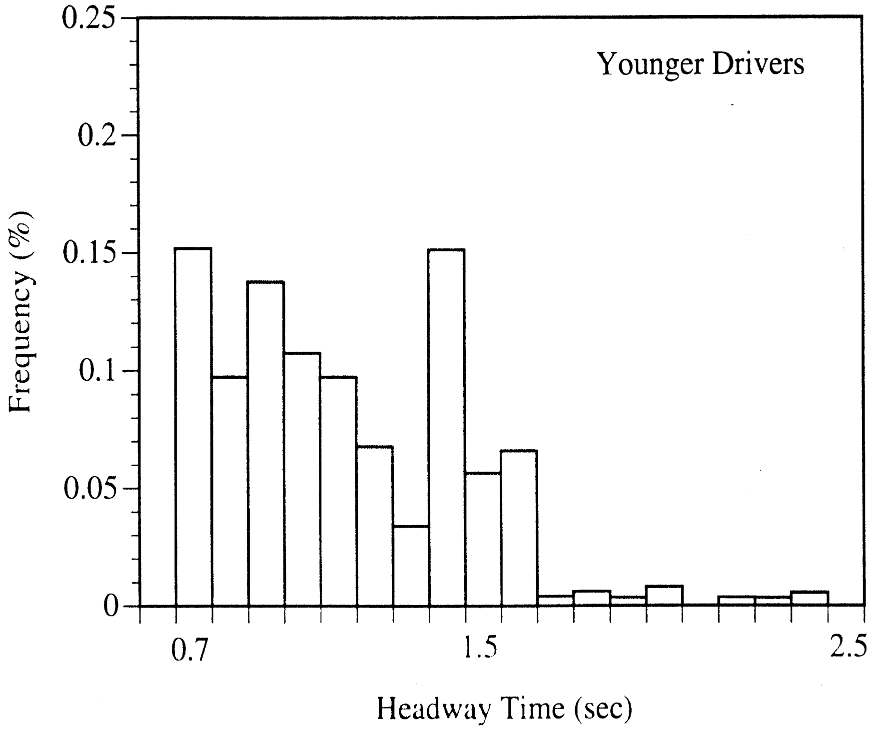


Figure 2.1 Selected Headway Times for Younger Drivers.

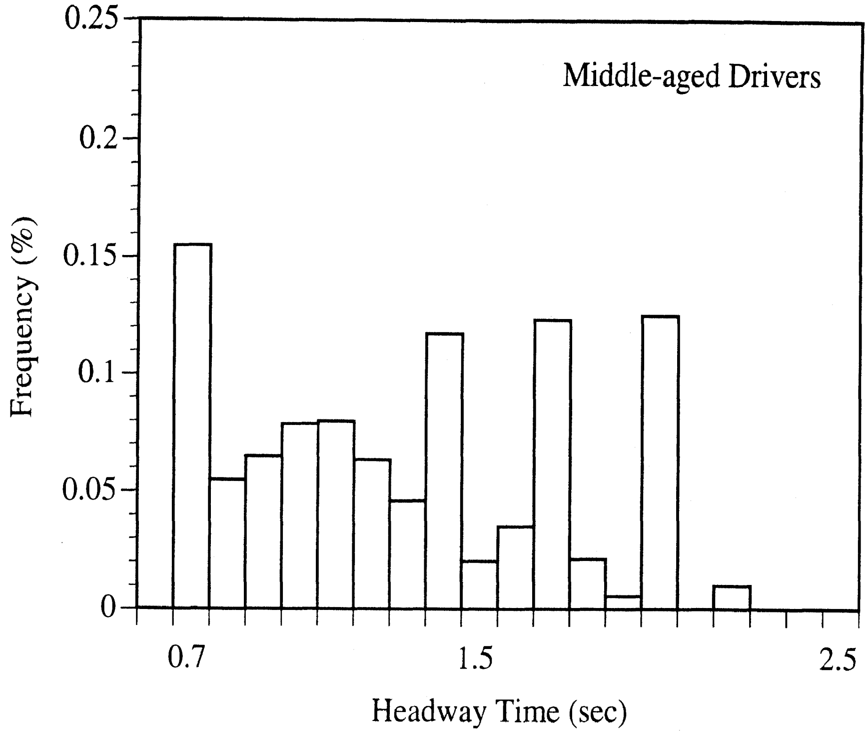


Figure 2.2 Selected Headway Times for Middle-Aged Drivers.

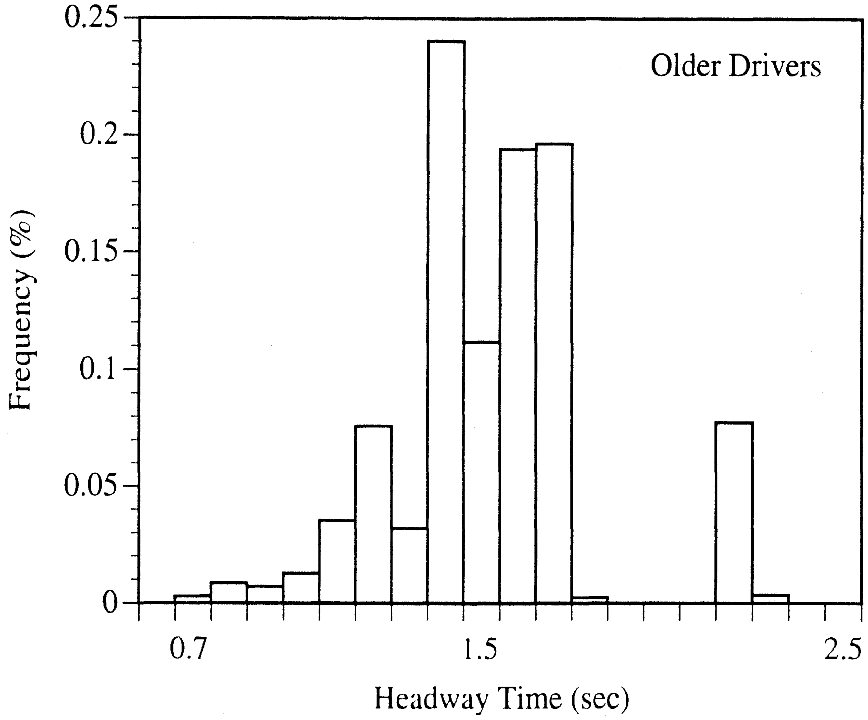


Figure 2.3 Selected Headway Times for Older Drivers.

In the modified method of adjustment participants drove at mean velocities ranging from 82.0 to 103.5 ft/second (mean velocities for young, middle-aged, and old age groups were 90.5, 93.0 and 86.3 ft/second respectively). The headway time that participants selected as a "comfortable" following distance ranged from 0.7 to 2.3 seconds (mean headway time for young, middle-aged and old age groups were 1.25, 1.53 and 1.87 seconds, respectively). A plot of the headway times determined by participants to be a comfortable following distance, and the mean velocity while traveling at that distance, is provided in Figure 2.4.

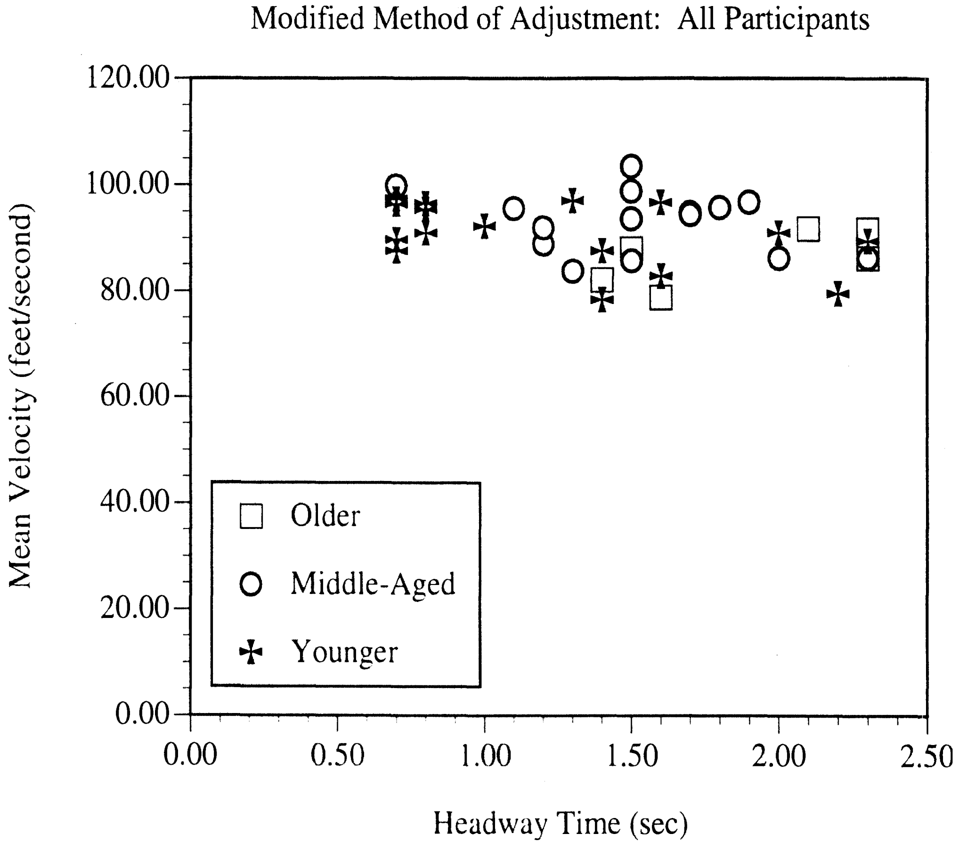


Figure 2.4 Mean Velocity vs. Headway Time Corresponding to Comfortable Following Distances - All Drivers.

2.4 Discussion

In general, the results indicate that many drivers tend to accept headways at or below 1.4 seconds, while the younger drivers are particularly inclined to prefer short headways (despite the occurrence of a floor effect in our experiments). In contrast, older drivers tend to prefer headways greater than 1.4 seconds. This finding corresponds to our previous results for manual driving. In effect, the adjustable headway feature (in contrast to our fixing of headway at 1.4 seconds in prior testing) appears to be preferred by drivers. Further, this feature is likely to lead to the selection of headway values that are much shorter than 1.4, as constrained by the lower bound of the adjustment device. (Note that in UMTRI's field operational test of intelligent cruise control [2], there are three choices of headway time setting available to the driver/participants; specifically 1.0, 1.4, and 2.0 seconds).

3.0 Classification of Drivers by Headway Time and Range Rate

3.1 Differences Between Manual And ACC Control Of Headway

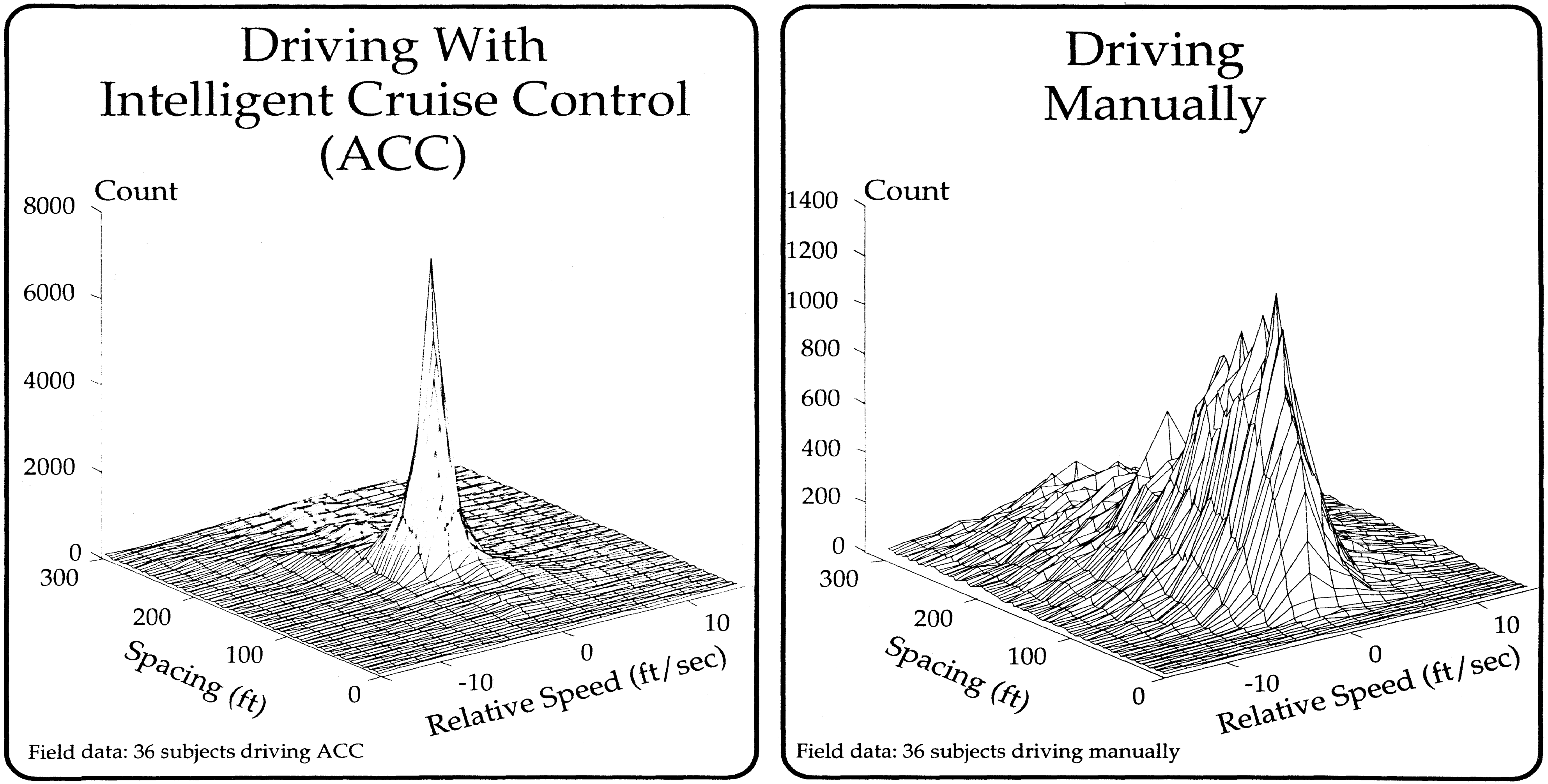
Control of headway is fundamental to the development of ACC systems. In evaluating these systems, there are questions regarding whether and which types of drivers will like the functionality provided by an ACC system. Results, obtained from processing data from driving on freeways, indicate that there are large differences between (1) how drivers control headway manually and (2) how a generic ACC system with limited deceleration authority controls headway. See Figure 3.1. Most of the drivers indicated that they liked the ACC system [1], even though it is clear that the ACC system tended to provide a much more consistent selection of headway and tended to interfere with any preference to operate at short headway spacing and to approach others at large negative relative speed (high closing rate). Some drivers comment favorably on ACC precisely because it does keep them from driving at the close headways and rapid closing rates such as they would have chosen if driving manually. Perhaps the drivers found that it was much less stressful (easier) to let the headway control system perform the sensing, deciding, and control-actuation effort needed to adjust headway. In any event, our test participants enjoyed using the ACC system.

The data given in Figure 3.1 illustrate several important and interesting points concerning the differences between manual and ACC control of headway.

The range (spacing) versus range-rate (relative velocity) histogram, Figure 3.1.a, shows that the ACC controller is very effective at achieving and maintaining a range of approximately 140 feet at a range-rate of 0. This is exactly how the controller should work for a headway time of 1.4 seconds, when the typical speed of vehicles on the freeways is 100 ft/sec.

While hindsight makes it seem obvious, there is not much to be gained by aggregating large quantities of headway-keeping data when the ACC system is in operation, once one has established that the controller functions as expected. (Nevertheless, one might still want to look for anomalous behavior when the ACC driver reacts to unusual circumstances.)

By comparing Figure 3.1.b with Figure 3.1.a, one can see that manual driving is not nearly as well organized as ACC driving. In addition, manual driving involves a considerable amount of driving at short range and relatively large closing rate compared to that observed for ACC driving. In a sense, it seems much easier to explain ACC driving than it is to explain manual driving. This is because it is difficult to identify the rules and control strategies employed by drivers during manual control of headway. After all, for much of the time the driver may not be really concerned with controlling headway as a specific objective. (Drivers experience many periods of time in which the prevailing headway seems just fine for now, whatever it happens to be.)



Driving With Intelligent Cruise Control (ACC)

Field data: 36 subjects driving ACC

Driving Manually

Field data: 36 subjects driving manually

3.1.a **3.1.b**

[ACC driving will make the spacing of traffic much more uniform and will moderate the speeds with which vehicles overtake one another]

Figure 3.1 Comparison of ACC and Manual Driving

In contrast, the ACC system is always diligent and vigilant in controlling headway. Furthermore, there is evidence in the human factors literature that indicates that people are not good at determining range-rate at relatively long ranges [3]. Given this limitation of the human driver, it may be difficult for people to maintain a consistent range on the order of 140 ft, even if they try.

The point is that the data presented in Figure 3.1 indicate that manual driving is difficult to understand and further research on manual driving is probably needed to aid in understanding how people perceive the differences between ACC and manual driving. The following material attempts to provide a contribution to the theory of driving by identifying pertinent characteristics of different types of drivers.

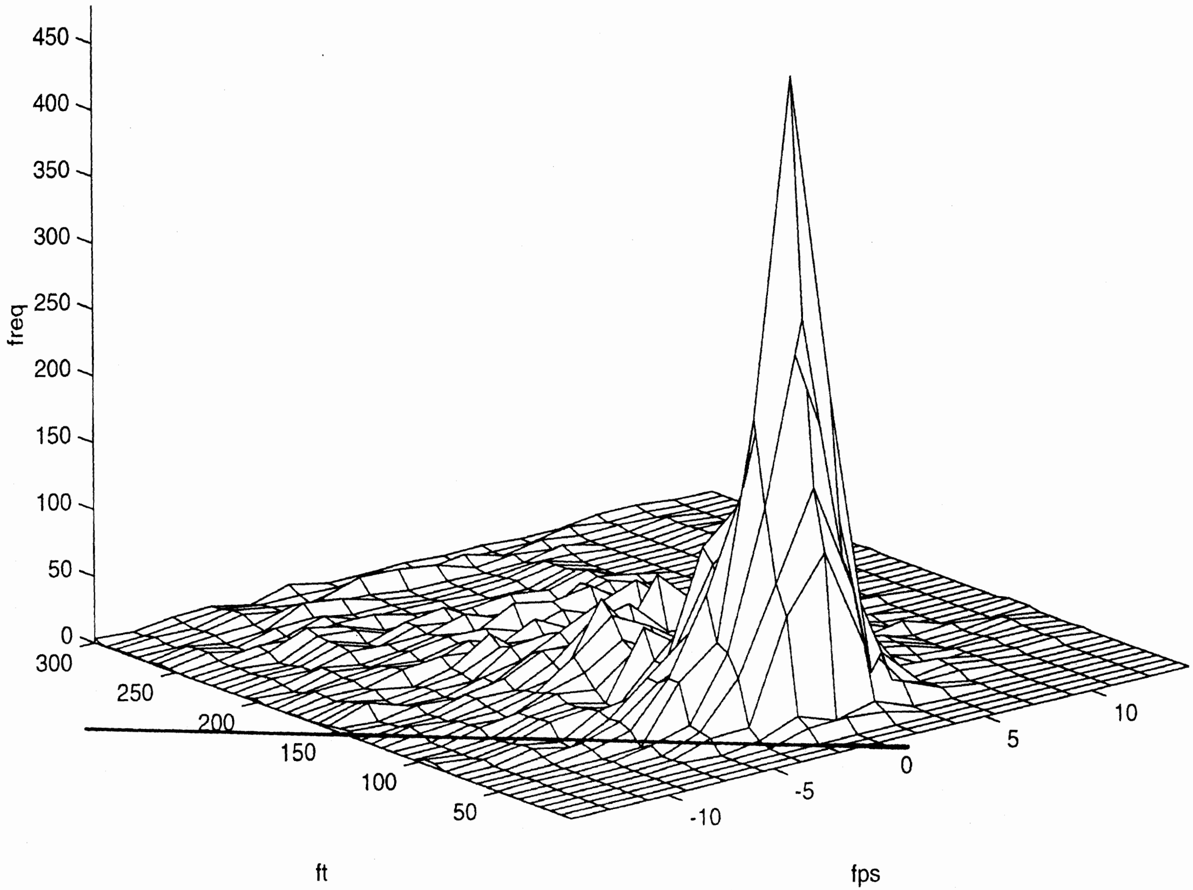
3.2 Range (R) vs Range-Rate (Rdot) Histograms for Different Drivers

While the previous Figure 3.1.b presented a histogram constructed from the data for 36 different drivers, one cannot assess the behavior of the individual drivers in this group from such a plot. However, the driving characteristics of individuals can be portrayed using individual histograms. The following examples, which are taken from Appendix A, characterize certain types of drivers.

The driving style of a rather typical young person in the 20 to 30 year age bracket is illustrated in Figure 3.2. This driver has a most likely value of available reaction time (Ta = R/V) of 0.6 sec.

Furthermore, there is a noticeable content of data having a time-to-impact (R/-Rdot for Rdot<0) of less than 10 sec. (See the 10 second time-to-impact line superimposed on the histogram of Figure 3.2.) Many of the drivers in the 20 to 30 year-old age range drive with the most likely value of headway time being less than one second. However, there is a distinct maximum "spike" in the frequency of range values (headway-distance) near zero range-rate. This spike represents the most likely value of this driver's performance in controlling headway. There is a striking similarity between the control performance of young drivers and the form of the control performance of the ACC system. In this sense, younger drivers perform like the ACC system except that the minimum headway permitted under ACC control in these tests was longer than that chosen by many of them. See Figure 3.3, which is a histogram for the set of 12 young drivers.

R vs Rdot for S2, N & Sort: V>=55*88/60 & Ltv==1 & (Lmch==0)



max @ fps=0, ft=57.41; Sum = 8954

Figure 3.2 Driving Style of a Younger Person.

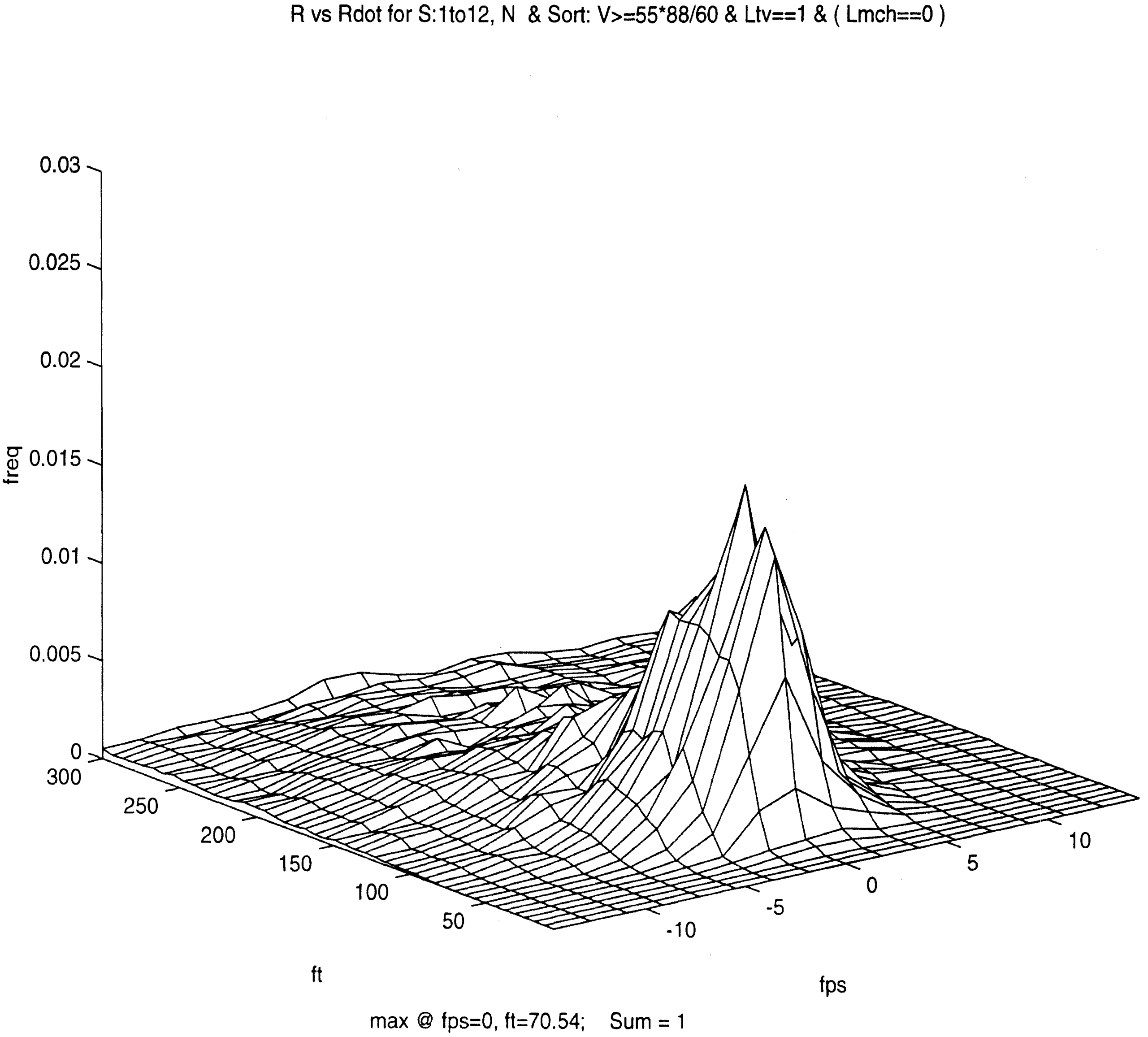


Figure 3.3 Group of 12 Younger Drivers.

Inspection of the full set of individual histograms reveals one driver whose headway control characteristics almost match those of the ACC system used in first year testing, with a most likely value of Ta (available reaction time) equal to 1.4 seconds. See Figure 3.4. Although the form of the histogram shows a dominant spike at 1.4 seconds, the magnitude of this spike appears at a much lower frequency of occurrence than that seen with the ACC system. Thus, the ACC system is much more consistent than this driver is, and, in particular, it avoids venturing into the shorter range domain, as exhibited in this manual case.

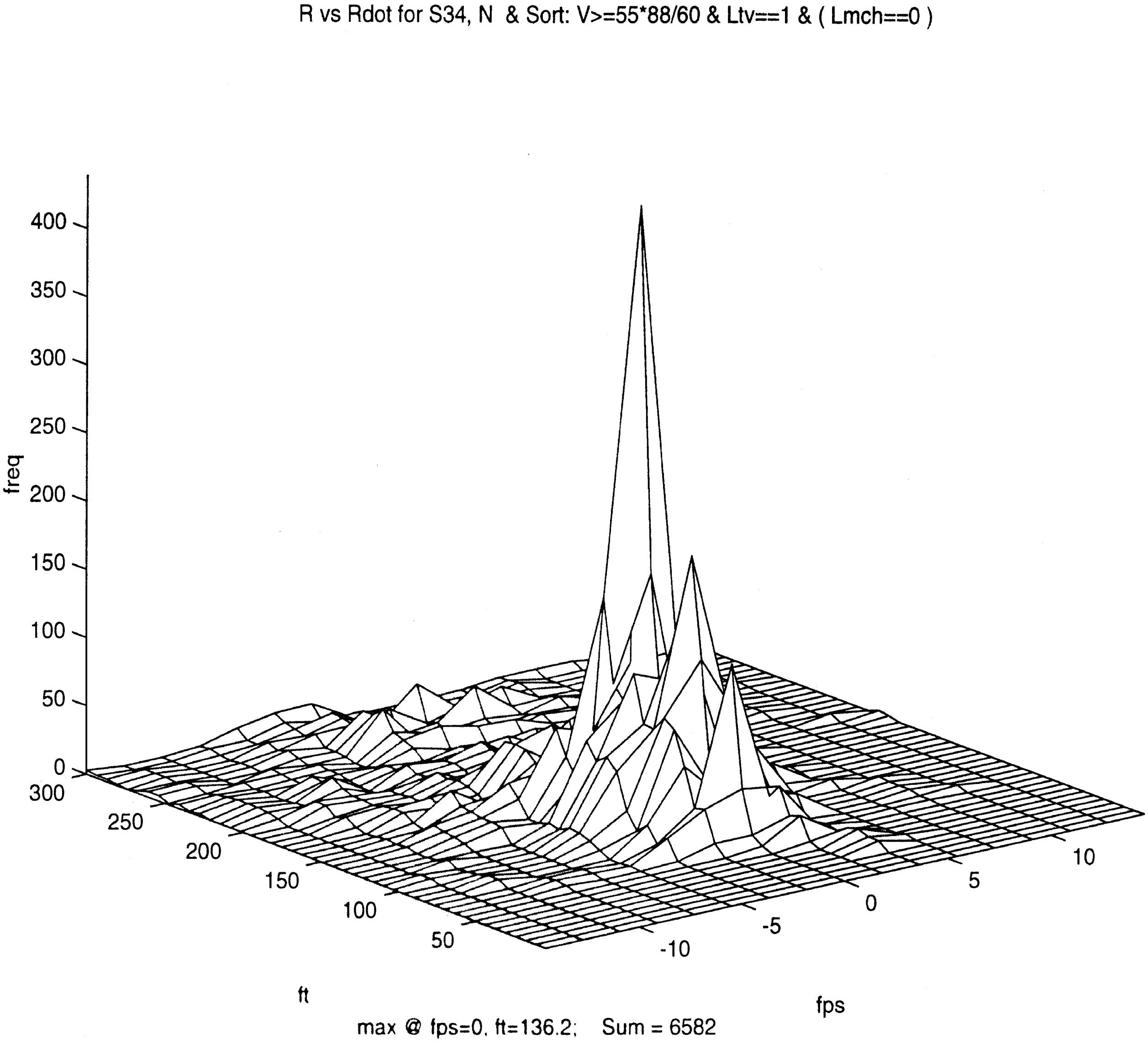


Figure 3.4 Driver with Most Likely Value of Available Reaction Time (Ta) Equal to About 1.4 seconds.

Figure 3.5 illustrates a driver that has a most likely value of available reaction time, Ta equal to 2.0 seconds. This driver operated with one of the longest available reaction times among those drivers that have one distinct value dominating their histogram.

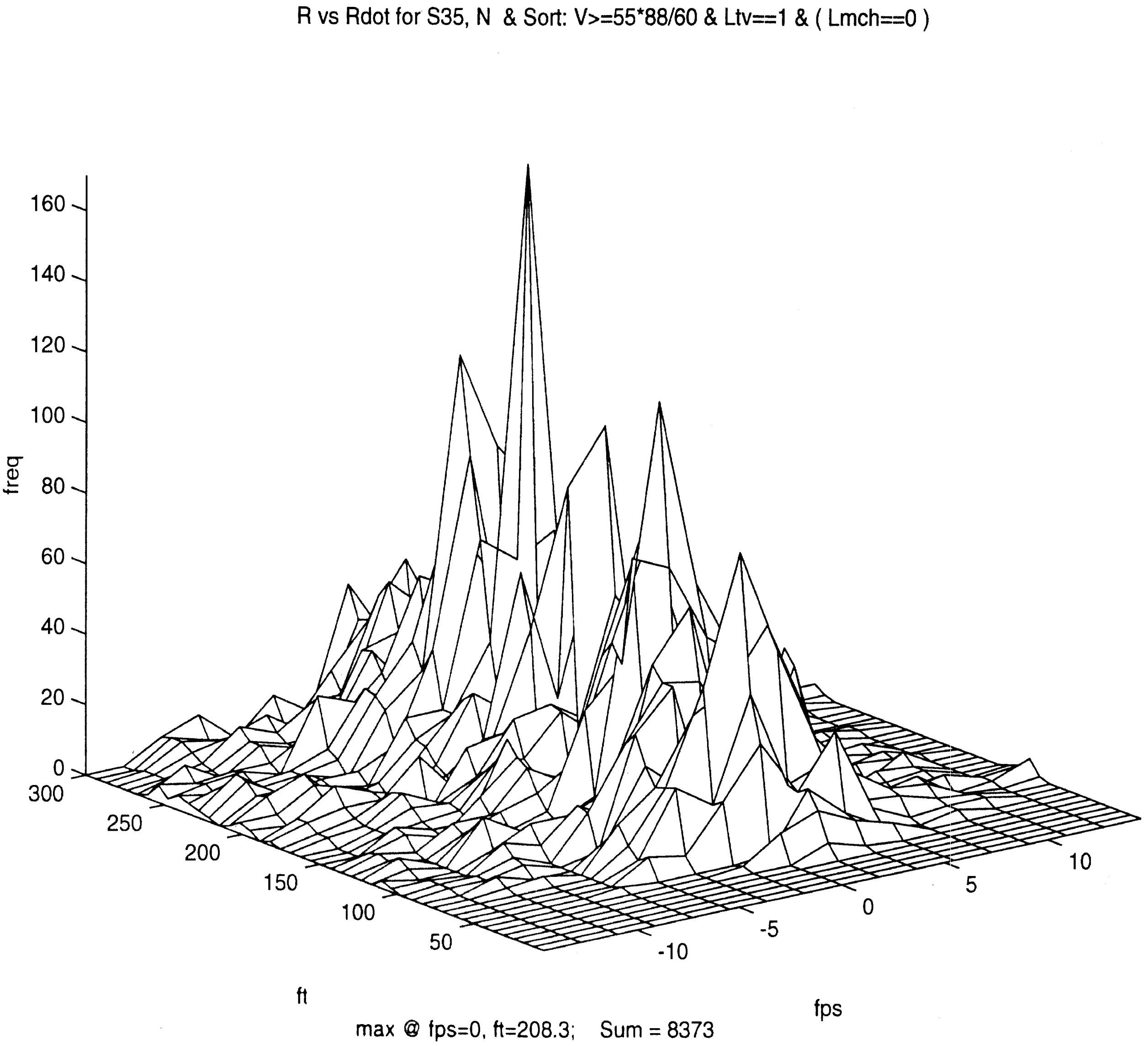


Figure 3.5 Driver with Ta Value Equal to About 2.0 Seconds.

Another type of driver has been observed who seems to be all over the range versus range-rate space. Such a driver appears to be very inconsistent and thus hard to predict in terms of headway choice. Figure 3.6 provides an extreme example of a driver who exhibits this type of behavior. (Perhaps many drivers feel that they often encounter others who behave in this manner.) Clearly, concepts such as most likely value are not especially appropriate for characterizing the driving results presented in Figure 3.6. (Nevertheless, the most likely value of headway time for this driver is included in the results presented in the next section.)

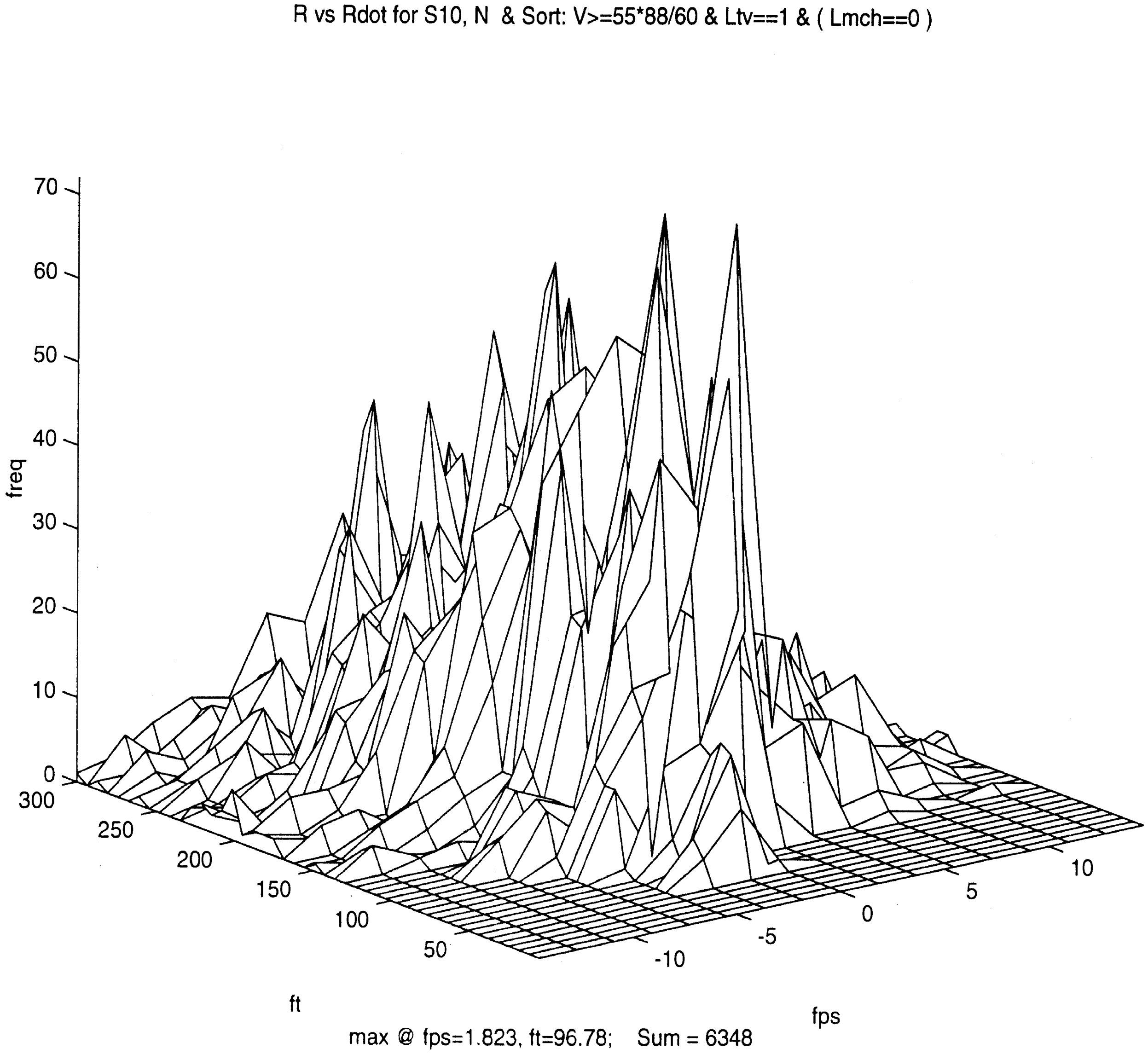


Figure 3.6 Inconsistent Driver.

The statistical results presented in the first annual report [1] indicated that differences between the driving performance of young drivers and older or middle aged drivers are statistically significant. No significant differences were found between middle aged and older drivers. Figure 3.7 is a histogram showing the aggregated performance of the middle aged and older drivers combined. By comparing Figure 3.7 with Figure 3.3, one can see the differences between the younger drivers and all of the other drivers.

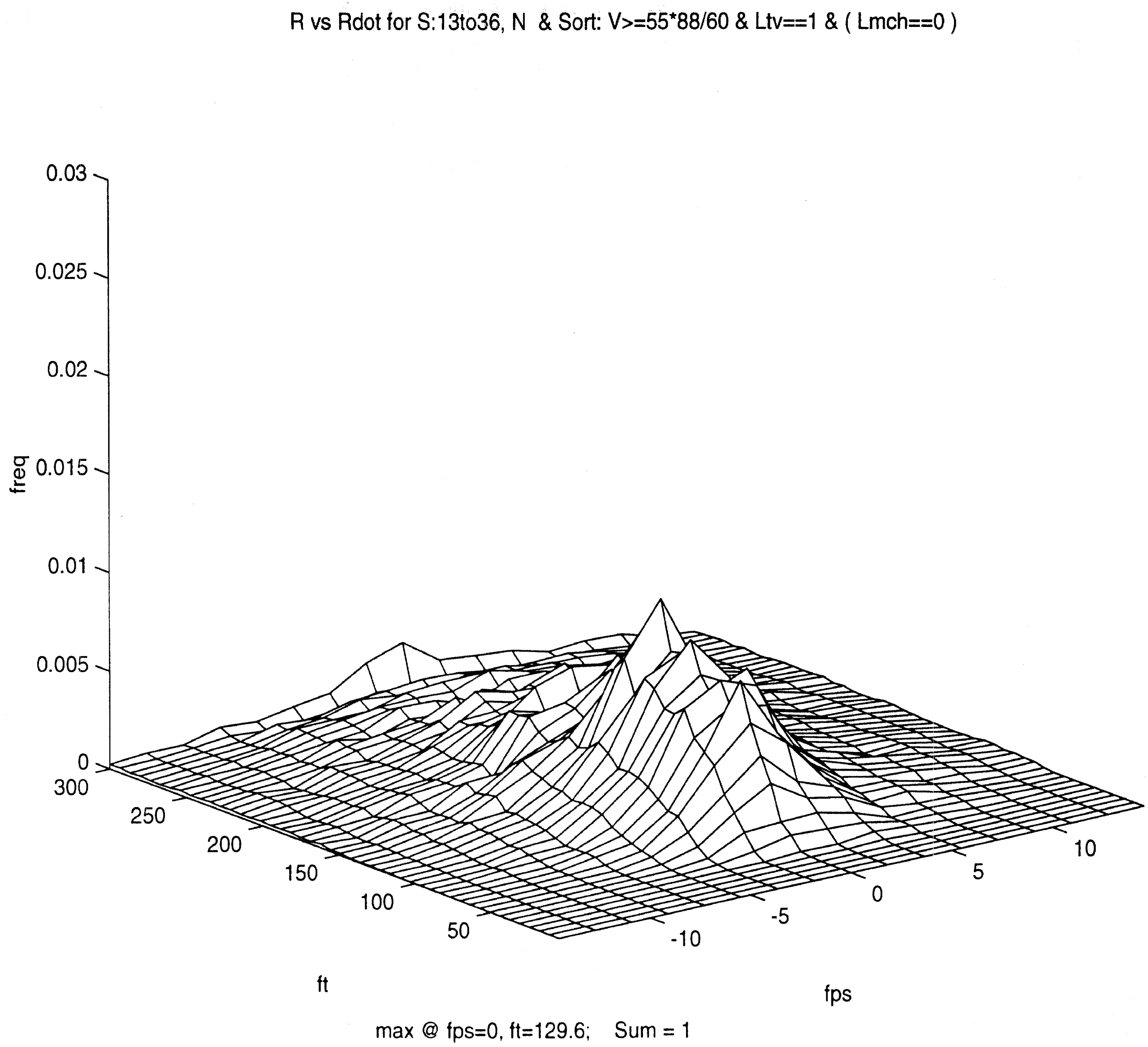


Figure 3.7 Group of 24 Middle-Aged and Older Drivers Combined.

In summary, Figures 3.1 through 3.7 show that there are different types of manual control of headway depending upon the driver. The histograms for individual drivers are not simply fuzzy versions of the composite histogram (Figure 3.1.b) for all drivers. The histograms for different drivers indicate the presence of various driving styles and patterns.

3.3 Findings Based on Rdot Average and Most Likely Headway Time

This section presents a scheme for identifying drivers as to whether they (1) travel at short headway and above average speed ("hunters"), (2) travel with the traffic flow at speeds and headways similar to most other cars ("followers" or "situation specific"), or (3) travel at longer headway and slower average speeds ("gliders").

The range-rate (Rdot) is the relative velocity between the driver/participant's vehicle and the preceding vehicle. Clearly, if the preceding vehicle is going faster than the driver's vehicle, the vehicles are separating and the range-rate is positive and the range is getting larger. People who tend to driver noticeably slower than most of the other vehicles on the road do not have many conflicts for space ahead of them because they rarely overtake anyone. Their driving task is relatively easier than that of a person who is continually overtaking other vehicles. Based on these simple observations, people who have a tendency to travel faster than the surrounding vehicles will tend to travel closer than people who travel slower than the surrounding vehicles. The slow travelers will seldom encounter short ranges except when someone cuts in on them and then only for a short time while the preceding vehicle pulls away from them. These simple ideas are the basis for identifying those drivers who tend to travel at speeds and distances that are different from the general flow of the traffic stream.

The concepts described in the previous paragraph can be quantified by using the average value of range-rate (Rdot) and the most likely value of available reaction time (Ta). Average range-rate is a measure of the driver's tendency to travel faster or slower than the preceding vehicles encountered by the driver. The available reaction time is a measure of how close to a preceding vehicle a driver is willing to travel. The most likely value of available reaction time indicates the amount of headway time that the driver employs most frequently. As indicated by the qualitative reasoning in the previous paragraph, it is reasonable to expect that people who tend to driver faster than the other vehicles on the road will also tend to drive closer to preceding vehicles. This discussion leads to the thesis that high negative levels of average range-rate and low levels of the most likely value of available reaction time are both indicators of attempting to travel faster than the general flow of traffic. It also indicates that positive values of average range rate and large values of the most likely value of available reaction time are indicators of attempting to travel more slowly than the general flow of traffic.

Figure 3.8 is presented to illustrate the application of this thesis to the headway control performance of the 36 drivers participating during the first year. The Figure has been separated into three regions illustrating a possible classification of drivers into "hunters," "followers," and "gliders." Hunters are those that attempt to travel faster than the flow of traffic in their lane. Followers tend to go with the flow of traffic. Gliders, in this terminology, are people who tend to travel noticeably slower than the other traffic on the road.

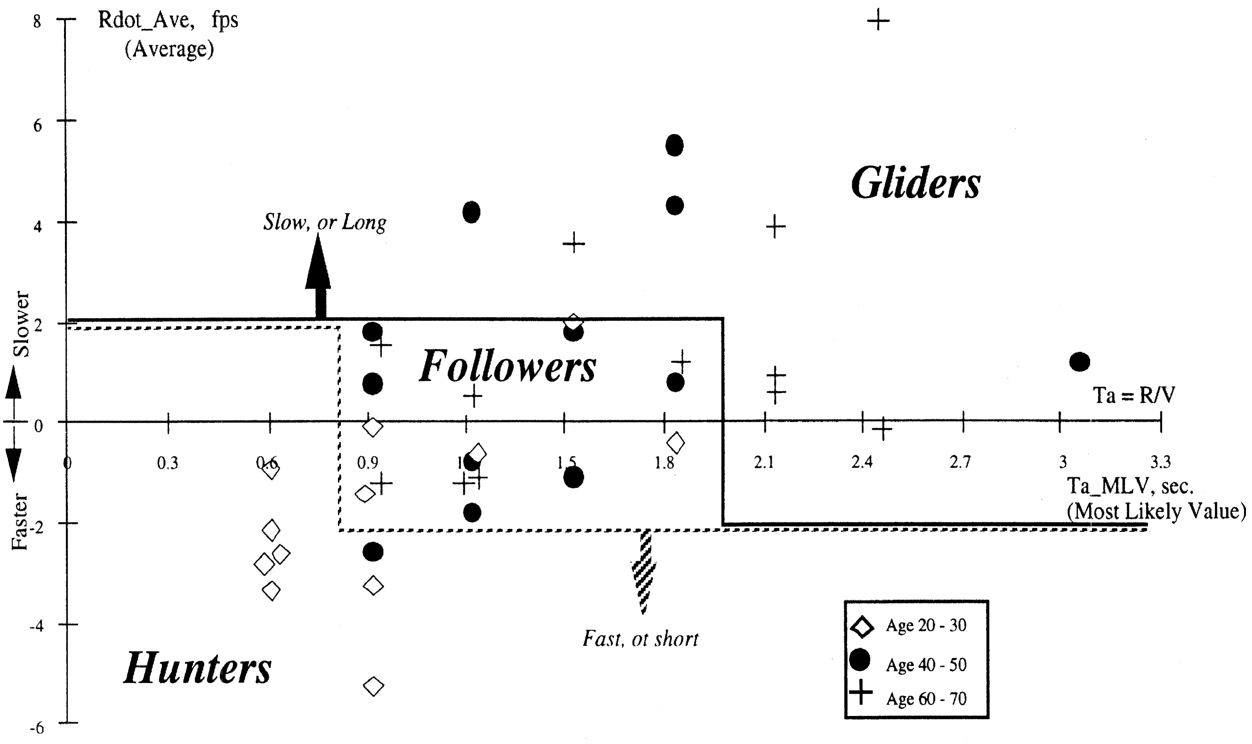


Figure 3.8 Hunters, Followers, and Gliders.

Examination of Figure 3.8 indicates that the set of 36 drivers has been divided into 8 hunters, 18 followers, and 10 gliders. Interestingly, all but one of the hunters comes from the group of 12 younger drivers. (Also, all but one of the younger drivers has a negative average range-rate indicating a tendency to travel faster than the other vehicles.) The followers are a mixture of all age drivers. The gliders are a mixture of older and middle age drivers. Gender does not matter in these results.

Composite range versus range-rate histograms for the hunters, followers, and gliders are presented in Figures 3.9, 3.10, and 3.11, respectively. These results illustrate the differences between the driving performance of hunters, followers, and gliders. They show that, although more consistent, ACC systems configured with headway times from 1.0 to 2.0 seconds will perform in a way that approximates the headway-keeping characteristics of the group of drivers classified as "followers." The ACC headway time of 1.4 seconds selected for the first year of this study (FOCAS) turns out to be nearly in the center of the follower range of performance characteristics.

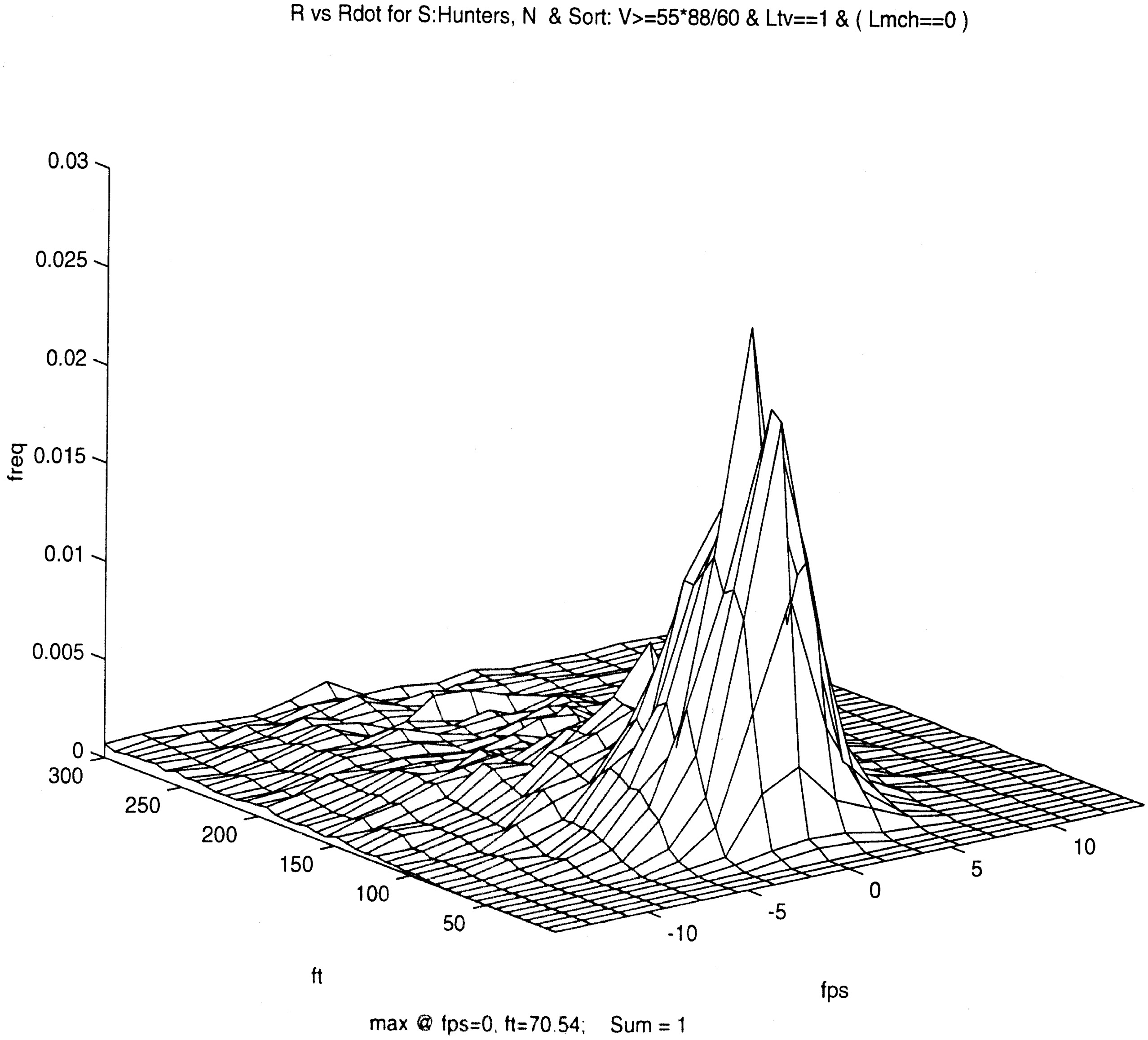


Figure 3.9. **Hunters.**

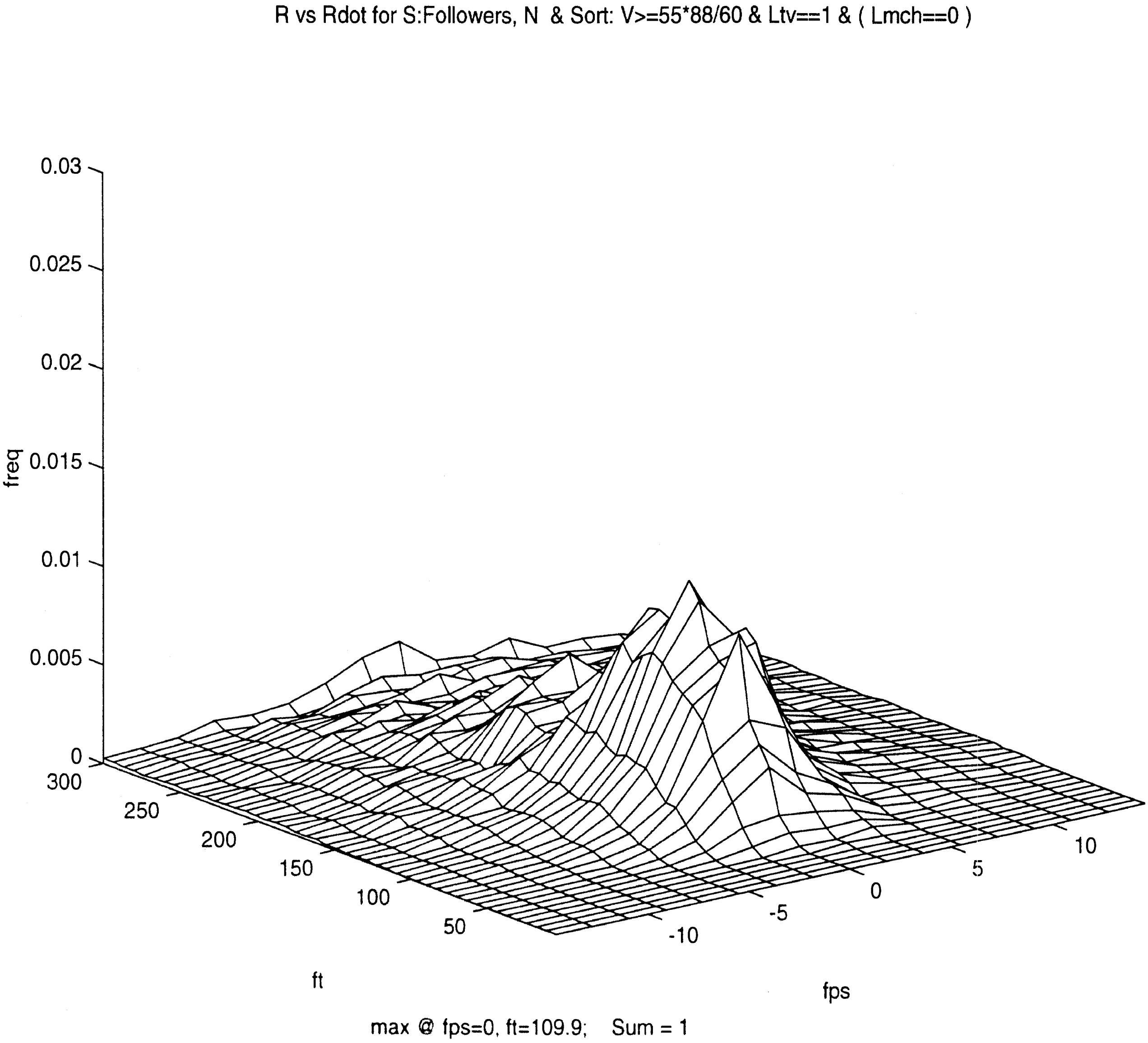


Figure 3.10 Followers.

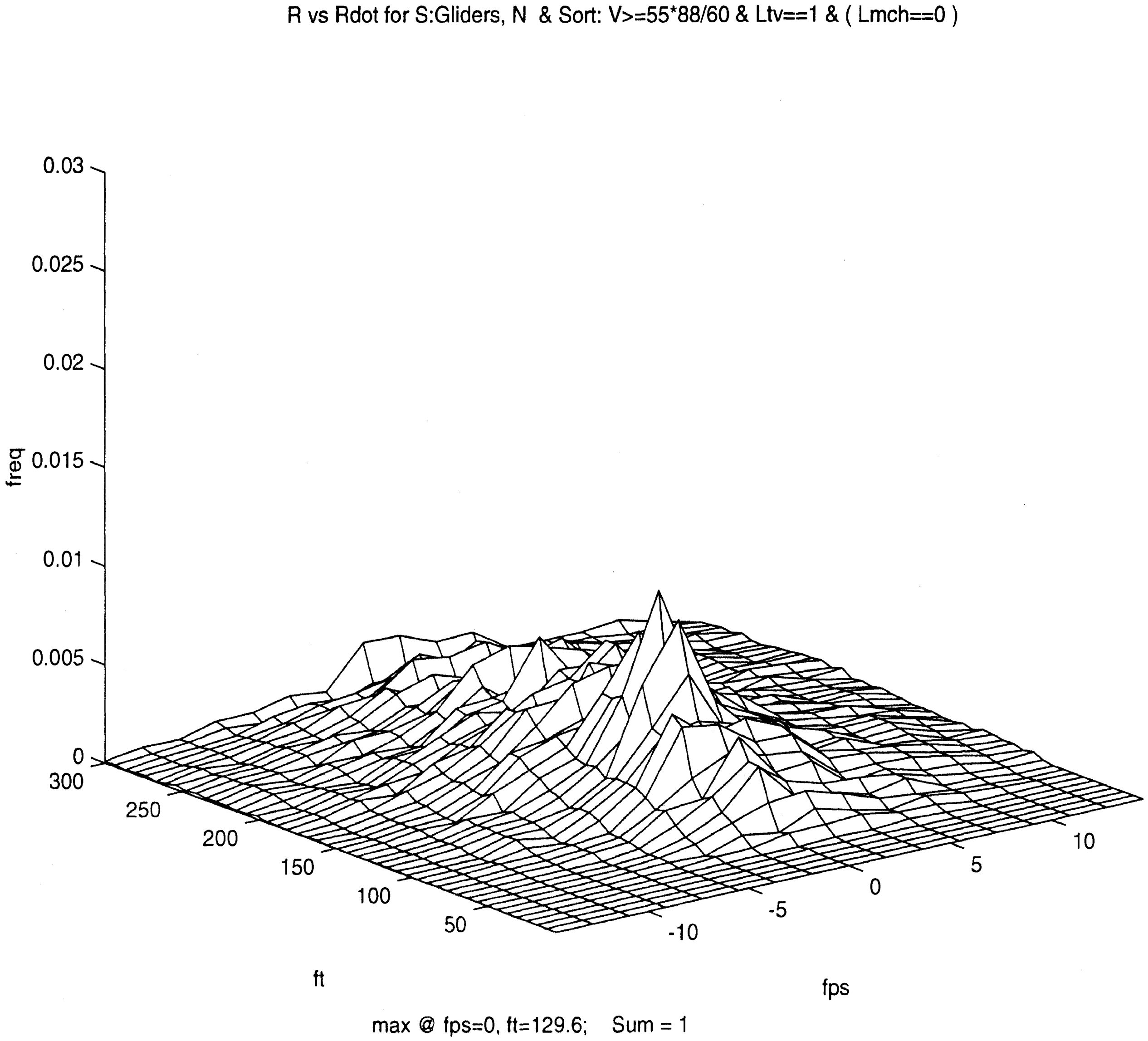


Figure 3.11   Gliders.

4.0 Methods for Finding Types of Driving Episodes

New analysis tools have been developed for use in evaluating the performance of FOCAS packages. One of these tools has to do with using neural network technology to identify different types of driving situations.

4.1 Overview

One method for identifying different types of driving scenarios that are captured within the FOCAS data stream is to apply neural network techniques for pattern recognition. Such approaches may be used to augment other data processing methods currently being used, and to provide additional analysis tools for streamlining the data interrogation process. Initial analyses have used neural net techniques to identify and classify different types of example driving scenarios (e.g., passing a target vehicle, closing in on a target, lane-changes, constant speed following, exit ramp encounters, etc.) based upon short sequences of driver/vehicle time histories recorded on board and then analyzed by a post-processing neural net program. (Future applications could also implement these types of algorithms on-board a vehicle in real-time to help existing software identify legitimate conflict encounters for such tasks as automatically triggering an on-board video capture, or, to simply help identify and log other categories of driving scenarios.)

4.2 Neural Network Approach

Initial data processing of the FOCAS data has used a neural network approach to examine only a portion of the 36-driver FOCAS data set. The basic technique involves training a neural network to identify patterns of on-highway driver/vehicle measurements (recorded by the on-board sensors) that represent likely categories of different driving situations. These measurement patterns are then associated with several corresponding driving scenario categories. (Currently, each pattern is defined as a collection of seven contiguous time history measurements, with each measurement component containing 20 seconds of distinct data sampled at 1 Hz.) The input to the network is a measurement pattern; the network output is a driving scenario category, as depicted in Figure 4.1.

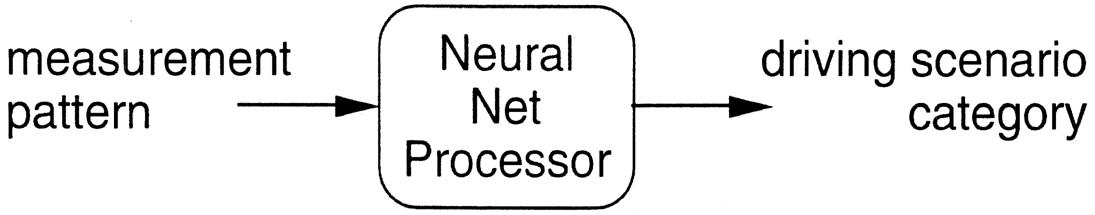


Fig 4.1 Neural Network Identification of Driving Scenarios.

A particular output category might be "closing in" or "constant speed following" or a "sudden merge." Eight such scenario categories were initially selected to test this concept (see Table 4.1).

Table 4.1 Example Driving Scenario Categories.

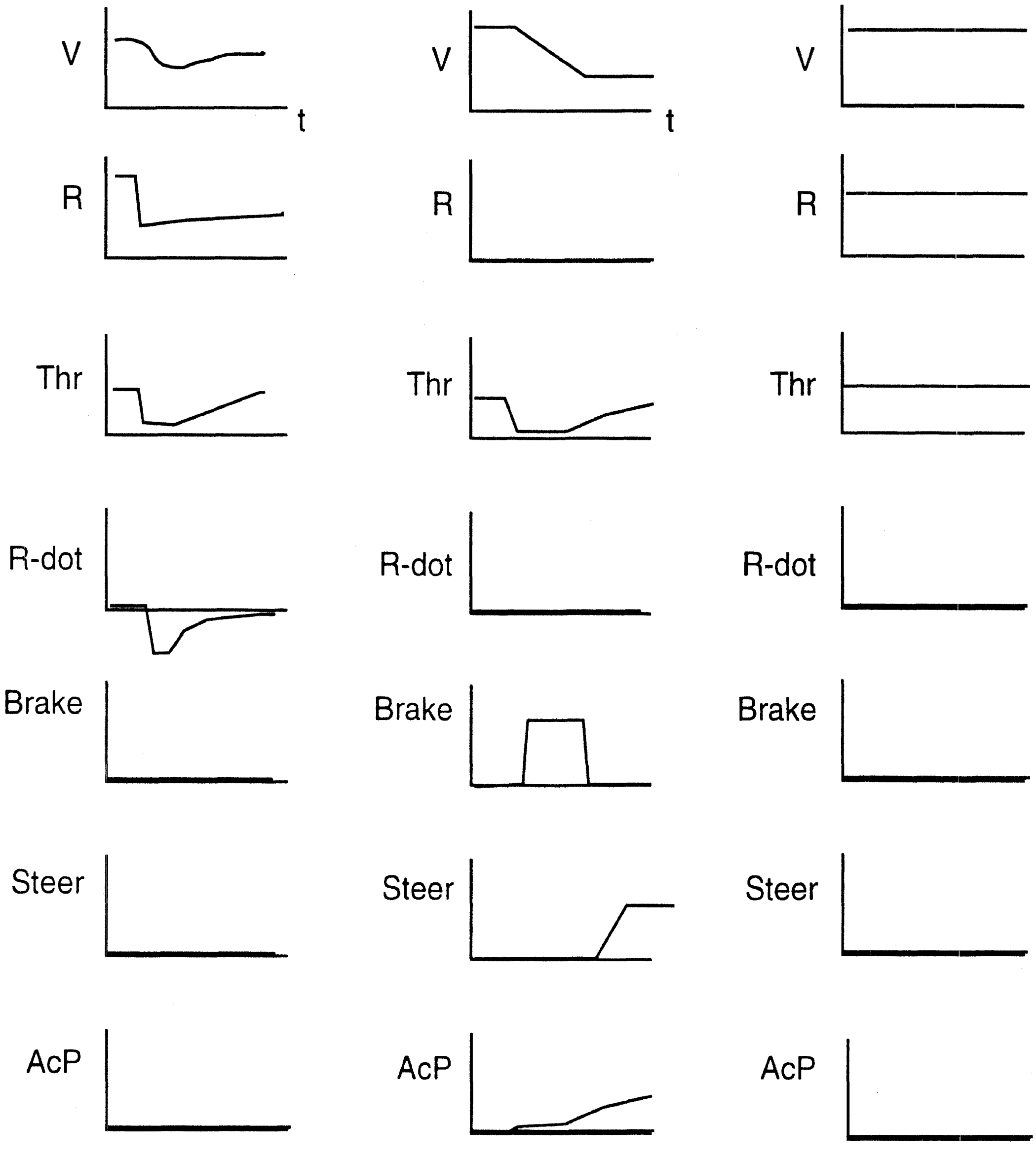
Scenario #	Description
1	**Sudden Merge** (by another target vehicle)
2	**Exit Ramp** encounter
3	constant speed **Following** of target
4	**Sudden Slow Down** (by lead vehicle)
5	**Closing-in** (by ACC vehicle on target)
6	**Chasing** (of lead vehicle)
7	**Cruising** (no target in range)
8	**Manual** interruption by driver

Figures 4.2a - 4.2c show example profiles of the types of waveforms expected to correspond to each of these different driving scenarios. The variables seen in each category are: 1) velocity of the ACC vehicle (V) , 2) sensor range measurement (R), 3) ACC system throttle position (Thr), 4) sensor range-rate measurement (R-dot), 5) driver brake actuation, 0/1 (Brake), 6) driver steering activity (Steer), and 7) accelerator position commanded by the driver (AcP).

Scenario #1, sudden merge, corresponds to cases in which a passing vehicle cuts in front of the ACC vehicle causing a sudden discontinuous jump in range, R, and a subsequent deceleration response from the ACC vehicle seen in V. Scenario #2 is simply an exit ramp encounter usually described by a declining velocity, a short brake application, and a significant ramp-step steering response. Constant speed following, #3, corresponds to constant headway tracking with a target engaged. Scenario #4, sudden slow down, applies to cases where the lead vehicle decelerates sufficiently that the ACC vehicle cannot produce enough deceleration by itself, thereby requiring a brake application by the driver. The closing-in scenario, #5, corresponds to cases where the ACC vehicle is travelling faster than the target and begins to overtake. Scenario #6, chasing, covers scenarios in which the ACC vehicle is engaged and accelerating due to the target vehicle travelling at a faster speed or accelerating. Cruising, Scenario #7, is the same case as constant speed following, except that no target is engaged (e.g., no immediate traffic is within range of the ACC sensor).

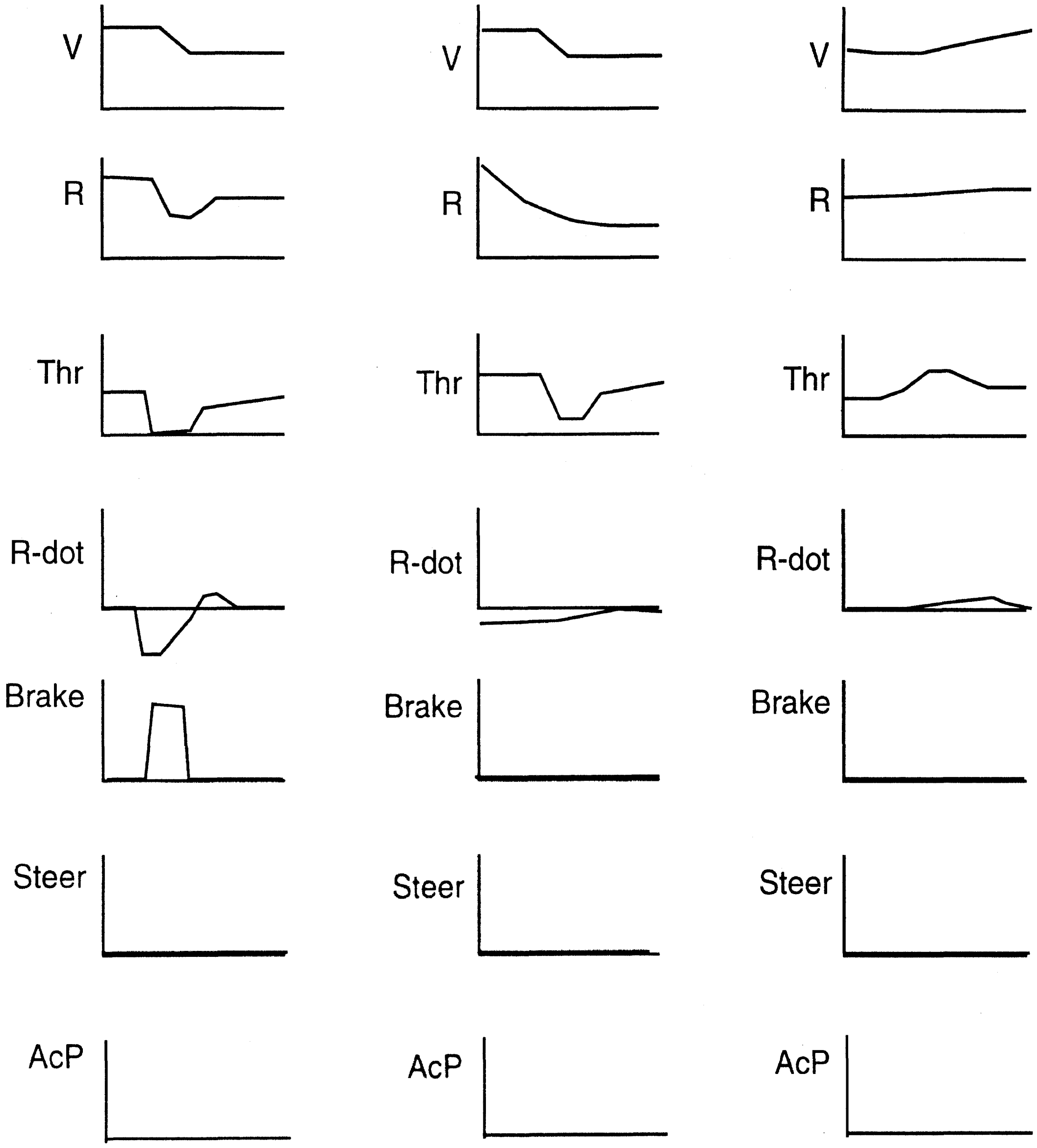
Lastly, Scenario #8, manual interruption, applies to cases in which the driver has interrupted the ACC system and is currently controlling vehicle speed (indicated by a non-zero acceleration position signal, AcP).

Each of these particular scenarios is an example of the types of driving behavior that can be encountered. Other scenarios, as well as variations on these examples, are also clearly possible. As additional experience is gained with the procedures described here, the analysis is likely to be refined further with additional driving scenarios being included. However, within the context of this report, only the eight cases described above will be used to illustrate the basic approach.



Sudden Merge ***Exit Ramp*** ***Following***

Figure 4.2-a. Example Waveform Profiles for Driving Scenarios.



Sudden Slow-Down ***Closing-In*** ***Chasing***

Figure 4.2-b. Example Waveform Profiles for Driving Scenarios.

A pattern (for use by the neural net) is then defined by combining these individual time histories contiguously, back-to-back, into one long waveform. By sampling each of these seven waveforms at 1-second or so intervals and combining that total information into one vector, a representative pattern for each particular driving scenario is defined. For example, if 20 seconds of each of the seven variables are sampled at 1-second intervals and then combined, the pattern vector would contain 140 elements. Multiple examples of each scenario are normally used during network training calculations in order to provide a sufficient variety of representative waveform characteristics, thereby helping the network classify similar patterns as belonging to the same category.

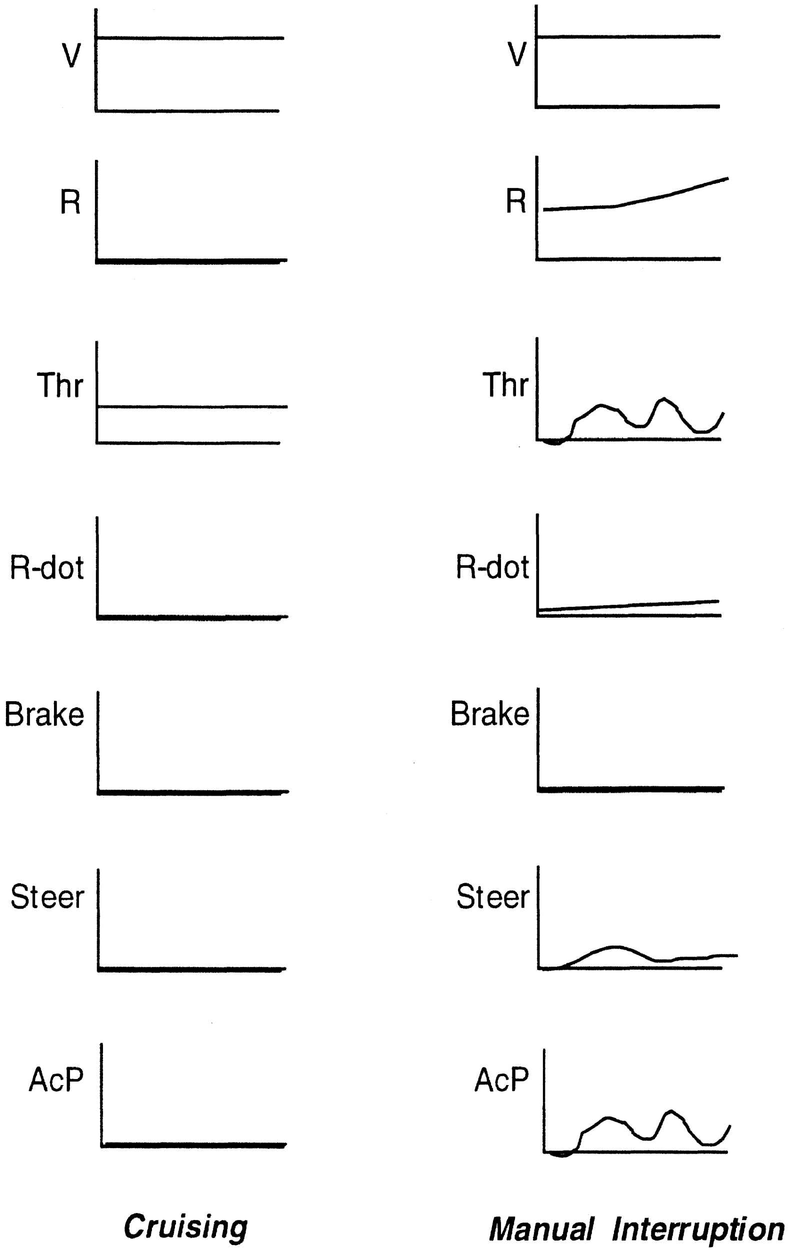


Figure 4.2-c. Example Waveform Profiles for Driving Scenarios.

The initial network architecture selected for this application is seen in Figure 4.3. It contains 140 input nodes (corresponding to the measurement pattern described above), 15 first-layer neurons, and 8 output-layer neurons (each associated with one of the driving scenarios of Table 4.1). A nonlinear sigmoid, defined in Figure 4.4, defines each neuron's activation function. This structure results in neuron outputs lying in the range from 0 to 1. At the output layer, a neuron value of 1, coupled with all other output neurons at zero, is defined as a recognition condition for that neuron containing the value of 1. For example, if the first output neuron is associated with the "sudden merge" driving scenario, then its activation at 1, and all others at 0, indicates the presence of a sudden merge scenario in the current input pattern.

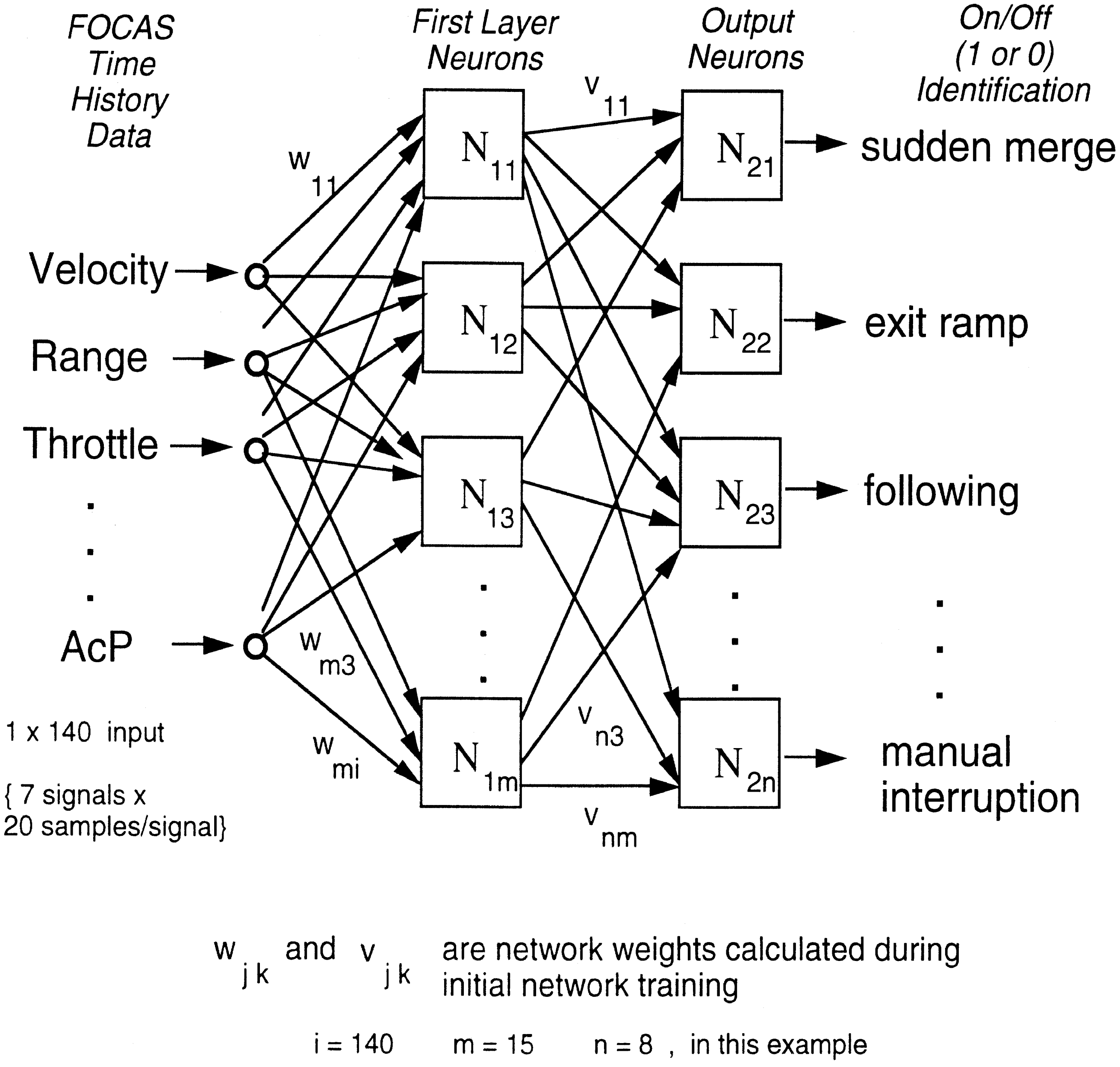
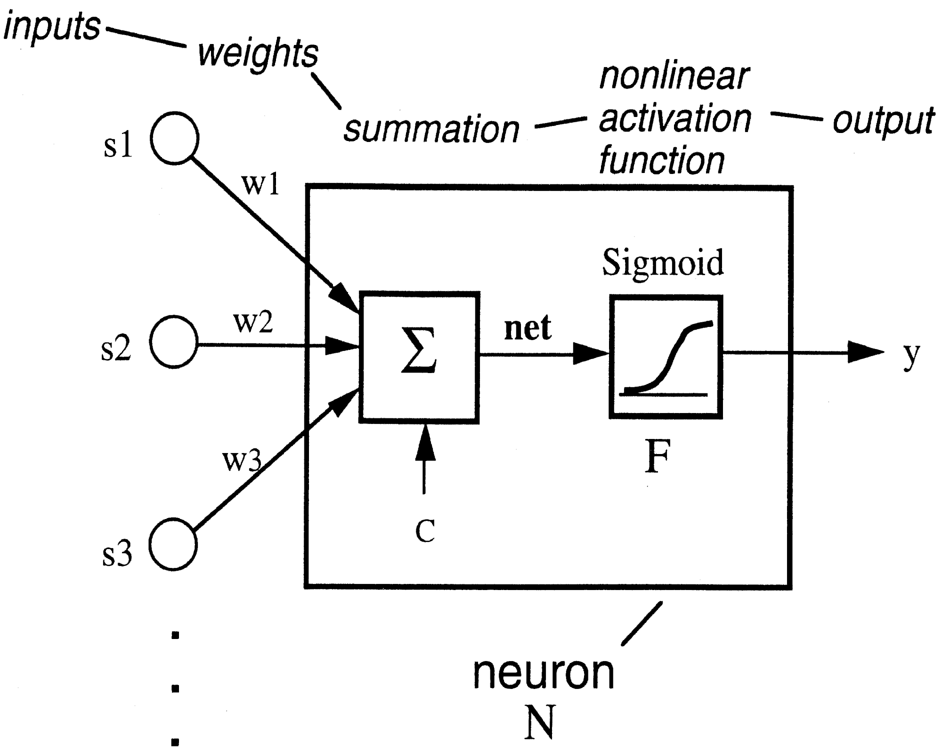


Figure 4.3 Neural Network Architecture used in FOCAS Classification Example.

Training of the network involves an iterative process by which pairs of input patterns and corresponding output training patterns are simultaneously presented to the network. For each input pattern presented to the network, a corresponding training pattern (comprised of 0's and a single 1 located at the neuron intended to be associated with that input pattern) is also required at the output layer. Network weight values are then iteratively adjusted until output errors (differences between what the network calculates at its output layer and the corresponding value of its output training pattern) are minimized. Without pursuing all the details, the process of network training ordinarily produces a set of weight values that then defines, in conjunction with the network architecture, the pattern recognition algorithm. This algorithm can then be used to process other input patterns, heretofore unseen, that are similar in nature to those input patterns used during the network training. If significant recognition problems are encountered with unseen data, additional training examples containing more variability, or alternate network architectures, or even different input categories, may be required.



$$\text{net} = \sum_i s_i w_i + c$$

$$y = F(\text{net})$$

$$F = \text{Sigmoid}(\text{net}) = \frac{1}{1 + e^{-(\text{net})}}$$

Figure 4.4 Nonlinear Activation Function Definition.

4.3 Example Results

To illustrate this procedure, actual samples from the FOCAS database are used here in place of the generic profiles described in Figure 4.2. The same scenarios and network architectures described above are used in the examples. Representative time histories of each on-highway driving scenario, described in Figure 4.2, were first identified manually within the FOCAS database to train the neural net described in Figure 4.3. Several examples of each of the eight categories were used in the network training sessions using a subset of data gathered from two drivers.

Sudden Merge Scenario

Figure 4.5 shows a set of four different FOCAS time histories for the range variable, R, corresponding to the sudden merge category (or output neuron #1). Each time history represents a specific occurrence of a sudden merge scenario. The time histories have been normalized so that their values lie approximately in the range of -2 to +2. Normalizing helps to display typical variations present in each signal on a similar numerical scale, and thereby reduces network training times. Each signal is sampled here at 1-second intervals across a total time interval or window of 20 seconds.

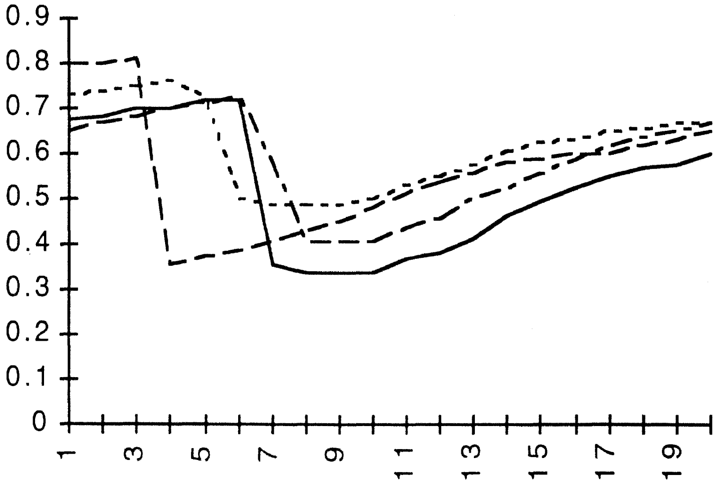


Figure 4.5. Sudden-Merge Examples from the FOCAS Database. Range / 200 (ft) vs. Time (sec)

Figures 4.6 and 4.7 contain corresponding time histories for the ACC throttle signal, Thr, and for velocity, V. These also have been normalized.

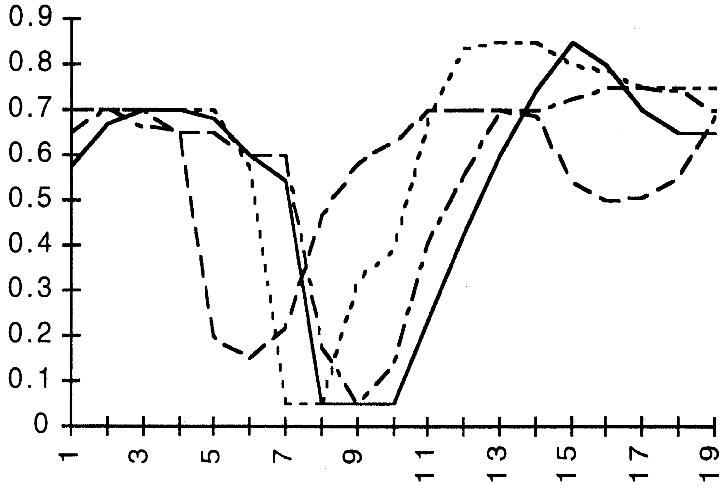


Figure 4.6. Sudden-Merge Examples from the FOCAS Database. Throttle / 20 (%) vs. Time (sec)

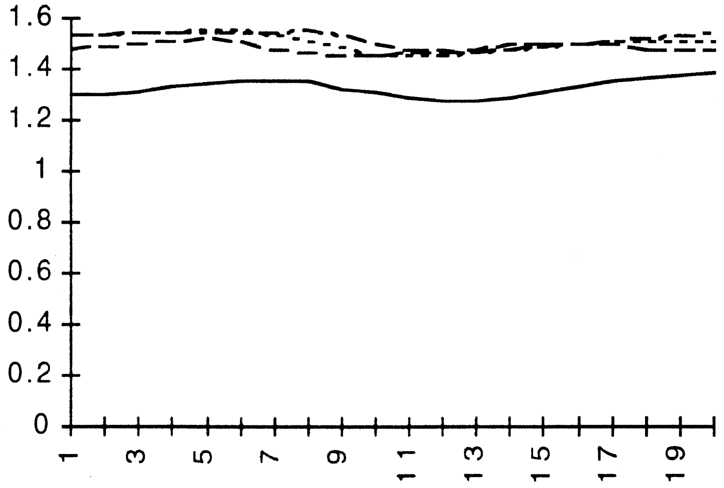


Figure 4.7. Sudden-Merge Examples from the FOCAS Database. Velocity / 66 (ft/sec) vs. Time (sec)

If these three sets of time history variables, and their four counterparts (not shown above), are combined end-to-end as a set of contiguous waveforms, input patterns used to train the neural net can then be formed. Figure 4.8 shows an example set of input patterns. The scale is compressed somewhat on this graph in order to show all time history variables on one plot. The individual signals comprising the total input pattern are identified at the bottom of the graph. The first 20 points correspond to velocity, V; the next 20 points to range, R; and so on. Each input pattern length is 140 samples (7 variables x 20 samples each). A small offset from zero appears in the steer variable portion of the pattern. This may be due to an offset in the transducer, or because the vehicle is in a mild curve when the sudden merges occur. Alternate scaling factors could be used for the R-dot and

Steer portions of the input pattern in this example if more emphasis on information contained in these signal variations was felt to be important. These particular scaling factors were selected as a compromise to account for the wide range of variations possible in these signals under different operating conditions (e.g., intermittent target acquisitions that may cause large fluctuations in R-dot, exit ramps requiring large steer responses, etc.). A desired goal should be to select a scaling factor that permits typical signal variations to be displayed on a common scale, while also avoiding frequent overloading or saturation when large signal excursions do occur.

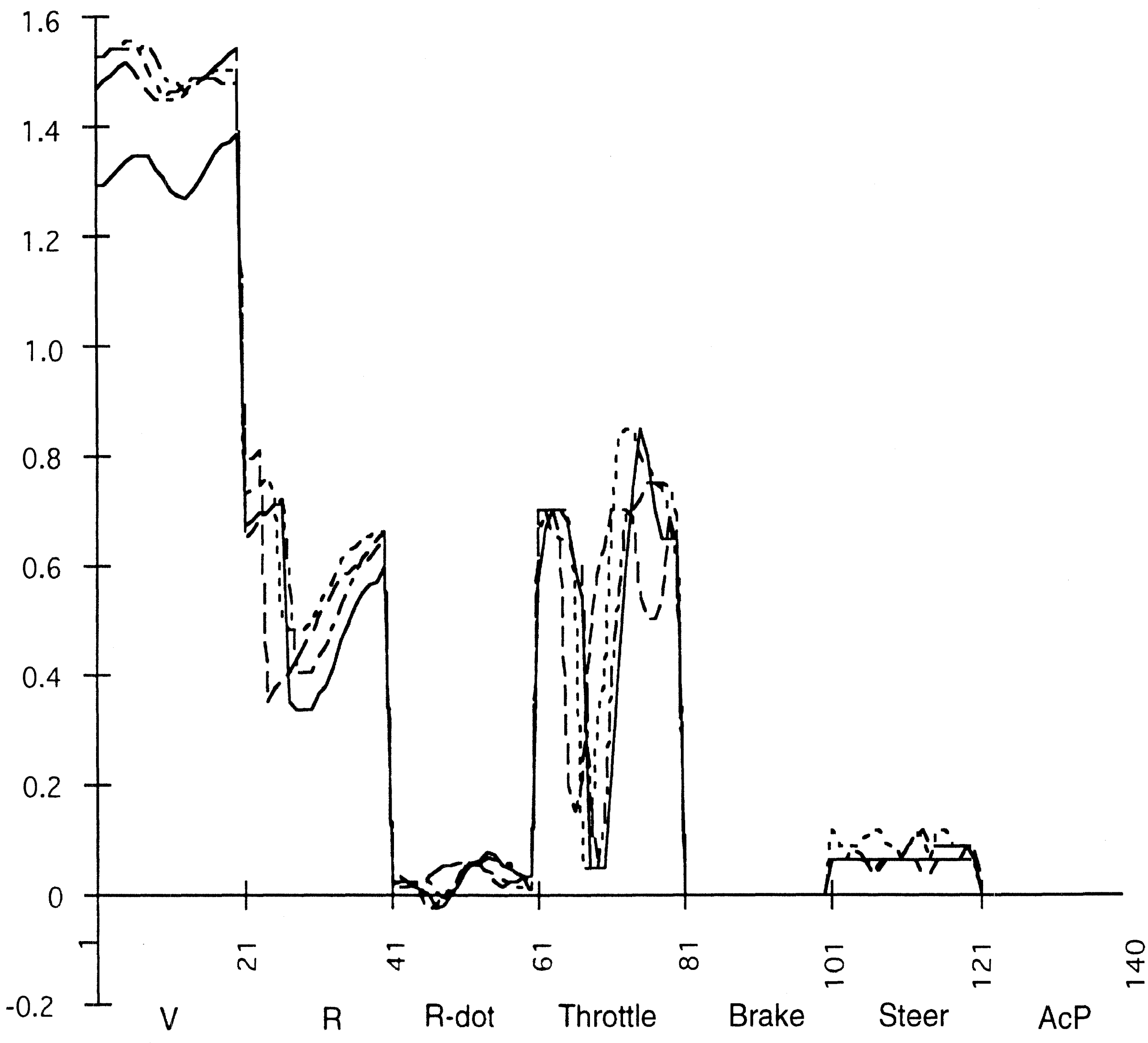


Figure 4.8. Contiguous Time Histories Assembled as Input Patterns to the Neural Network (Sudden Merge Scenario — Overlay of 4 Training Patterns).

Exit Ramp Scenario

This same procedure is now applied to three cases of exit ramp encounters. Figures 4.9 - 4.11 again show time history plots of range, throttle, and velocity. Driver brake response and steering behavior are also shown in these exit-ramp examples in Figures 4.12 and 4.13.

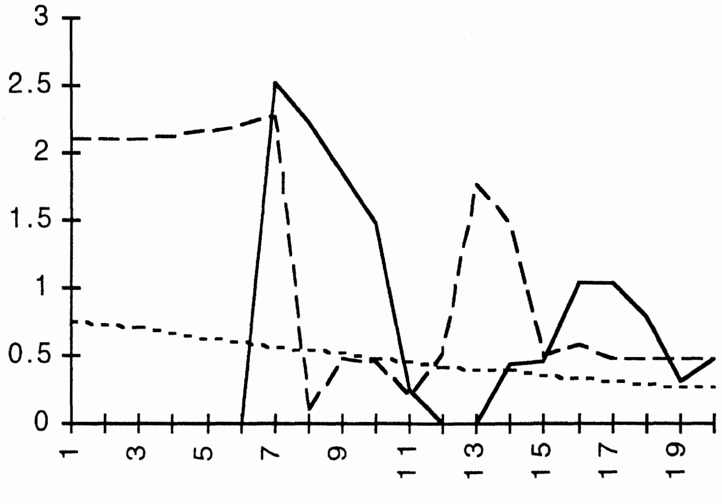


Figure 4.9. Exit Ramp Examples from the FOCAS Database. Range / 200 (ft) vs. Time (sec)

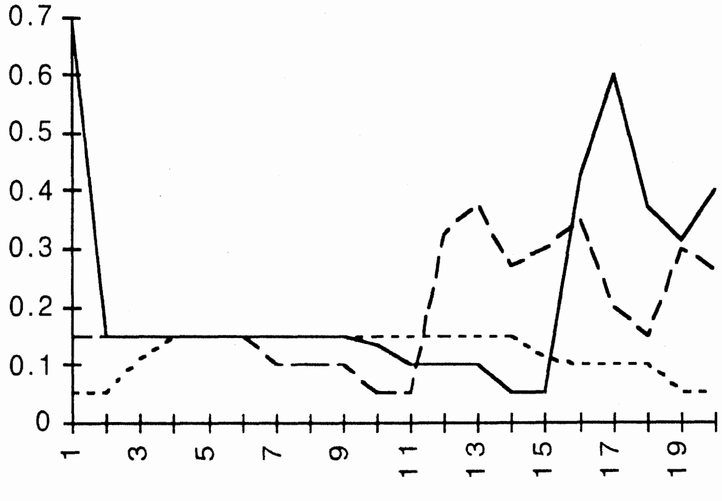


Figure 4.10. Exit Ramp Examples from the FOCAS Database. Throttle / 20 (%) vs. Time (sec)

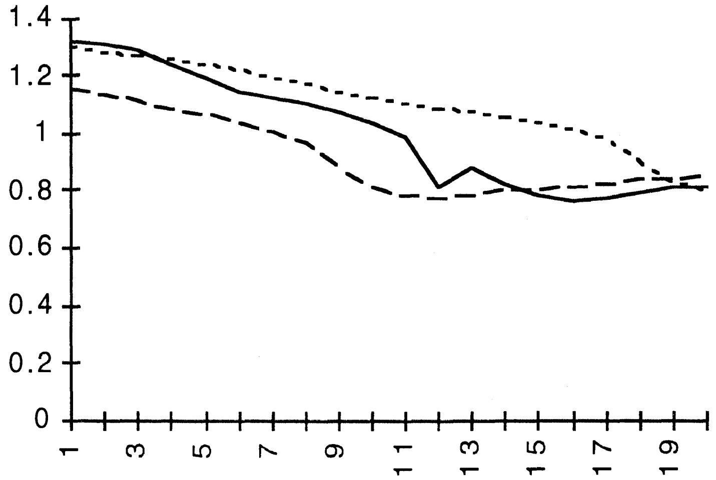


Figure 4.11. Exit Ramp Examples from the FOCAS Database.
Velocity / 66 (ft/sec) vs. Time (sec)

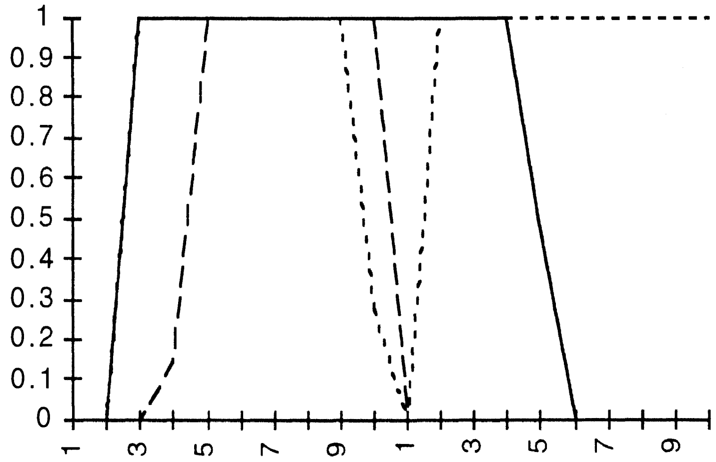


Figure 4.12. Exit Ramp Examples from the FOCAS Database.
Brake (On / Off) vs. Time (sec)

As in the previous example, these individual time histories can be combined as a contiguous input pattern for network training. Figure 4.14 shows the resulting input pattern for the exit ramp scenarios obtained from this assembly procedure (analogous to that seen above in Figure 4.8 for the sudden-merge scenario).

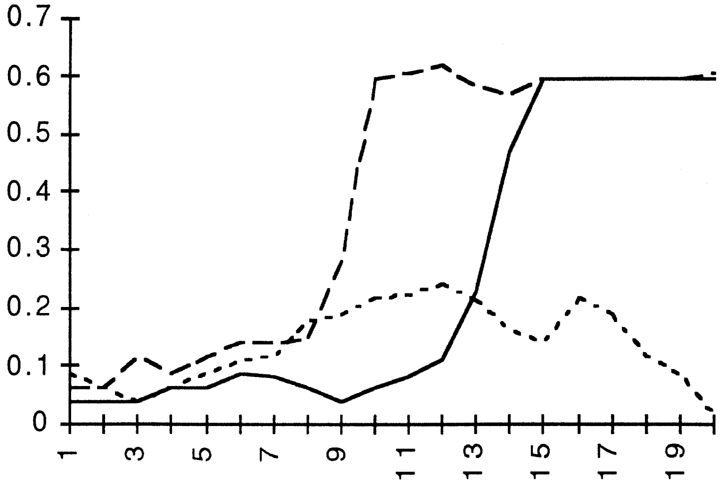


Figure 4.13. Exit Ramp Examples from the FOCAS Database. Steer / 100 (deg) vs. Time (sec)

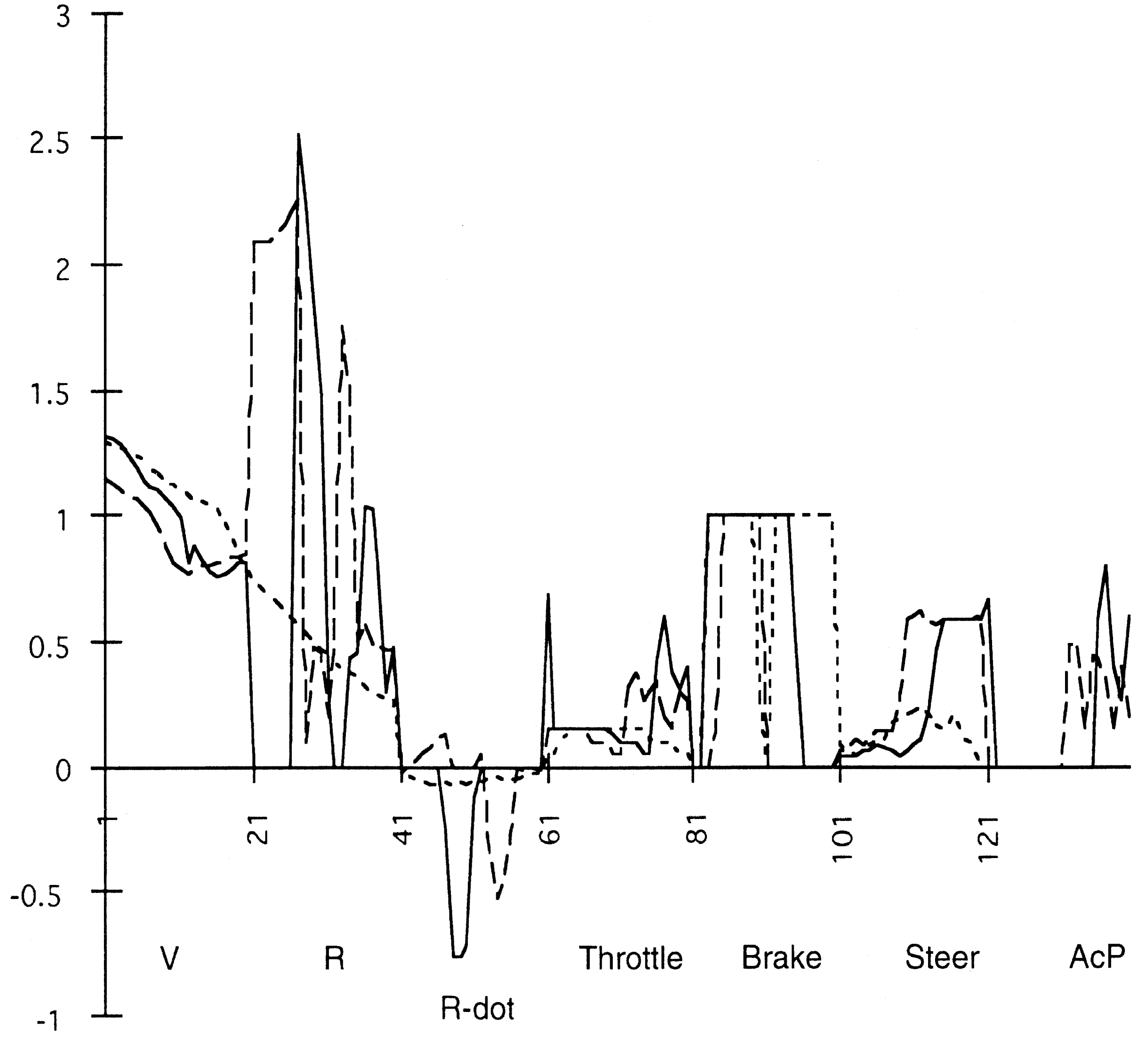


Figure 4.14. Contiguous Time Histories Assembled as Input Patterns to the Neural Network (Exit Ramp Scenario — Overlay of 3 Training Patterns).

This type of procedure was then repeated to collect training sets for each of the other six different driving scenarios described in Table 4.1. In this particular example exercise, 8 input training patterns were identified for the sudden merge category; 4 patterns for the exit ramp category; 4 for constant speed following; 2 for sudden slow down; 6 for closing-in; 6 for chasing; 5 for cruising; and 9 for the manual interruption category. This produced 44 total input training sets. Output training patterns (8 x 1 vectors) comprised of all zeros except for a single 1 at the corresponding output neuron, were also created and used with the above input patterns during network training.

The accuracy of the network following training was evaluated by having the neural network reprocess the original data, plus additional data sets from several other drivers. In general, about 80 to 90 percent of the categories from new data sets and different drivers (not previously seen during training) were correctly identified by these initial trials. (An example calculation is described below.)

Network training times for these initial examples were a few minutes using an average desktop computer and MATLAB. The processing time (following the neural net training) to examine an hour's worth of FOCAS data (also using MATLAB) for one driver was also a few minutes. These processing times would be expected to increase somewhat, if subsequent network architectures became more complex or if the number of additional training samples increased. This is not expected to be a problem since significant performance gains can be achieved by moving the present processing code to faster machines and/or coding the neural net algorithms directly in C.

Figure 4.15 shows a sample listing of results obtained from processing a 60-second portion of the FOCAS database with the neural network following its training with the above input patterns. The first column shows time from the start of the database. This time also corresponds to the start of the 20-second window for which neural net calculations are to be performed. The next eight columns correspond to the numerical values of the eight output layer neurons calculated by the neural net algorithm (using this 20-second window of data). The last column is a simple description of the event identified at the current reference time. Only those cases in which one output neuron is close to 1.0 (+/- 0.02) and all other output neurons are approximately 0.0 (+/- 0.02) are reported in this output log. The 0.02 threshold value for filtering output reports is somewhat arbitrary and could be selected as a larger value to include additional cases. Lowering the threshold value helps to eliminate false identifications; too small a value can result in under-reporting.

In this example processing, identifications were reported for approximately half the database content, with about 80 to 90 percent accuracy (based upon informal re-inspection of results). Cases that were mis-identified usually related to categories that had similar profile definitions such as "following" and "chasing," where the primary distinction is often dependent upon the constancy of one or two waveforms (velocity and range in these cases).

```
Time                        Output   Neurons                     Meaning
(sec)     1        2        3        4        5        6        7        8
                             (Calculated Values)
970.00 0.0005 0.0000 0.0000 0.0005 0.0000 0.0004 0.9992 0.0002  cruising
971.00 0.0005 0.0000 0.0000 0.0004 0.0000 0.0007 0.9991 0.0002  cruising
972.00 0.0005 0.0000 0.0000 0.0004 0.0000 0.0017 0.9993 0.0001  cruising
975.00 0.0003 0.0000 0.0000 0.0002 0.0000 0.0109 0.9990 0.0001  cruising
981.00 0.0009 0.0000 0.0000 0.0000 0.0000 1.0000 0.0002 0.0009  chasing
982.00 0.0001 0.0000 0.0000 0.0000 0.0000 1.0000 0.0000 0.0008  chasing
983.00 0.0000 0.0000 0.0000 0.0000 0.0000 1.0000 0.0000 0.0001  chasing
984.00 0.0001 0.0000 0.0000 0.0000 0.0006 1.0000 0.0000 0.0000  chasing
985.00 0.0001 0.0002 0.0000 0.0000 0.0003 1.0000 0.0000 0.0000  chasing
986.00 0.0003 0.0000 0.0000 0.0000 0.0019 1.0000 0.0000 0.0000  chasing
987.00 0.0001 0.0000 0.0000 0.0000 0.0027 1.0000 0.0000 0.0000  chasing
988.00 0.0000 0.0000 0.0004 0.0000 0.0055 1.0000 0.0000 0.0000  chasing
999.00 0.9965 0.0000 0.0000 0.0056 0.0002 0.0000 0.0000 0.0005  sudden merge
1002.00 0.9983 0.0000 0.0000 0.0032 0.0000 0.0000 0.0001 0.0010  sudden merge
1003.00 0.9976 0.0000 0.0000 0.0032 0.0000 0.0000 0.0052 0.0030  sudden merge
1006.00 0.0001 0.0000 0.0000 0.0000 0.0000 1.0000 0.0013 0.0100  chasing
1007.00 0.0000 0.0000 0.0000 0.0000 0.0000 0.9999 0.0004 0.0052  chasing
1008.00 0.0000 0.0000 0.0000 0.0001 0.0000 0.9997 0.0002 0.0042  chasing
1019.00 0.0012 0.0003 0.9980 0.0000 0.0003 0.0001 0.0000 0.0006  following
1020.00 0.0007 0.0004 0.9988 0.0000 0.0022 0.0001 0.0000 0.0003  following
1023.00 0.0004 0.0002 0.0023 0.0000 0.9954 0.0010 0.0000 0.0002  closing-in
1024.00 0.0004 0.0002 0.0013 0.0001 0.9986 0.0007 0.0000 0.0003  closing-in
1025.00 0.0003 0.0003 0.0012 0.0001 0.9992 0.0006 0.0000 0.0003  closing-in
1026.00 0.0003 0.0003 0.0010 0.0002 0.9995 0.0005 0.0000 0.0003  closing-in
1027.00 0.0003 0.0003 0.0008 0.0002 0.9995 0.0005 0.0000 0.0004  closing-in
1028.00 0.0003 0.0003 0.0006 0.0001 0.9995 0.0005 0.0000 0.0004  closing-in
1029.00 0.0004 0.0002 0.0004 0.0001 0.9994 0.0006 0.0000 0.0004  closing-in
1030.00 0.0004 0.0002 0.0004 0.0001 0.9994 0.0006 0.0000 0.0004  closing-in
```

Figure 4.15. Example Output Log / Index for 60 Seconds of FOCAS Data Processed by Neural Net Algorithm.

In the example listing seen in Figure 4.15, the sequence of identifications by the neural net could correspond to a sequence of driving scenarios where the ACC vehicle was first traveling without a target present (cruising), then acquired a passing vehicle in the left lane (chasing), followed by another vehicle that was then acquired by the ACC vehicle at a shorter range (sudden merge). The passing vehicle may have then slowed down resulting in it being tracked temporarily (following) and then gradually overtaken (closing-in) by the ACC vehicle.

The real utility, however, of this neural net indexing capability, may be its ability to locate and count occurrences of specific events of interest. For example, how many times did sudden merges occur and where in the database do they appear? Answers to questions like these may be of the greatest use initially.

4.4 Future Activities

Current plans are to improve the reliability of the neural net approach by including example training data from several more drivers and then to apply the same analysis to the entire set of 36 drivers. Since there are three groups of basic driving styles classified as "hunter," "glider," and "follower," data from two or three drivers from each group may be used to construct the training patterns. This would help expose the network to as much variation as possible for each scenario during network training sessions.

In another application, neural net analyses may also be used to help identify the "hunter," "glider," and "follower" driving styles, particularly for the non-ACC or manual driving portion of the FOCAS database. This could enable a neural net to process a few minutes or so of on-highway data from any driver and then to identify and categorize a driving style that best reflects that data segment. Initial network training would be based upon a cross-section of representative driver-vehicle responses reflecting these basic driving styles. Most drivers exhibit each of these three behavior patterns at various times. The definition applied to a specific driver probably reflects that driver's tendency to exhibit one style more frequently than the others, on average, over longer stretches of time.

If achievable, this analysis approach may be used to repeatedly sample batches of several minutes worth of driver-vehicle data and keep a running tab of driving style itself as a function of time. The output from this analysis, a graph (or some equivalent) of driving style versus time, could have three levels corresponding to the hunter/glider/follower categories. Plots, such as driving style versus time, may then help analysts better understand and correlate changes in driving style with traffic conditions or other driving environment factors that are encountered during the course of normal driving. This type of information could also be useful for helping design adaptive features into future ACC systems that might wish to support driver expectations of system operating characteristics under different driving conditions. An example might be an ACC system capable of modulating its operating characteristics based upon prevailing traffic conditions, roadway types, or other external factors sensed by the system.

5.0 Cues for Warning the Driver

By providing cues to warn drivers, ACC systems can significantly improve forward crash avoidance performance. Using the available information from the forward-looking sensor and combining it with known dynamic parameters of the host vehicle, such systems can evaluate the necessary response required to avoid a crash with the preceding vehicle. Once the necessary response is determined to be beyond the system's capability, a warning to prompt driver intervention can be invoked.

Within the framework of this project, several cues to prompt driver intervention were considered. These cues are staged so as to imply the response severity that is required: from merely calling driver's attention to the forward scene, up to an automatic application of braking.

The initial (i.e., first-year) design of the headway-control system was discussed in detail in Section 2.2 of the first-year report [1]. The objective of the system was to obtain and maintain the desired headway by means of commanding various speed values (V_C), which are translated by the OEM engine controller in order to modulate the throttle. When acceleration was called for, throttle setting was increased to some new value between its present position and its full-throttle application; similarly, when the vehicle was required to slow down, the throttle was retarded to be set between its present and its idle-speed position. At full coastdown (throttle closed to idle), the maximum deceleration was approximately 0.05g.

Thus, during the first year of this project, longitudinal control authority given to the ACC system was limited to throttle manipulation. Brakes were not applied automatically to control speed and no active warning signal was given to the driver. Nevertheless, a most elementary and basic form of warning cue was, indeed, built-in to the system's design. Namely, warning was provided implicitly through the kinesthetic cue arising from throttle modulation. Under most operational conditions, the speed of the vehicle was smoothly governed by small modulations of the throttle. When the prevailing conditions called for coastdown with a fully retarded throttle; however, it caused a momentary disruption in the smoothness of the drive, which was altogether noticeable. This initiation of coastdown served as a warning cue, alerting the inattentive driver to all situations challenging the control authority of the ACC system.

This section presents the various warning cues and the associated severity levels of required intervention, as expressed in terms of sensor data and vehicle dynamics.

5.1 Audio Warning Cue

During most of the time when the ACC system is engaged, throttle modulation can provide enough control authority to maintain the desired headway. The engine can provide enough acceleration force to close the gap on a departing vehicle. Similarly, if the preceding vehicle decelerates at a moderate level, the engine can provide enough retardation force to back-off and increase the gap as needed. Full retardation was obtained when the throttle was completely closed, and the vehicle coasted down. The audio-warning cue, which was incorporated into the design of the controller, activated a buzzer when the engine retardation at coastdown was not enough to operate within a safe headway distance.

Figure 5.1 depicts the audio warning design principle incorporated into the basic headway-control system. The straight line represents the control objective of the headway-control system. The system attempts to follow the straight line of the control objective, and to converge to the desired headway. Other design parameters in the figure are:

- D_C — maximum deceleration level under full coastdown (0.05g)
- α — fraction of the desired range.

The value of α is determined according to design preferences: it represents the shortest range for operation without a warning. Warning is issued if the system predicts, or if the data indicate, that the headway gap will become shorter than $\alpha \cdot R_h$. These design parameters have pre-set values that are part of the headway-control algorithm.

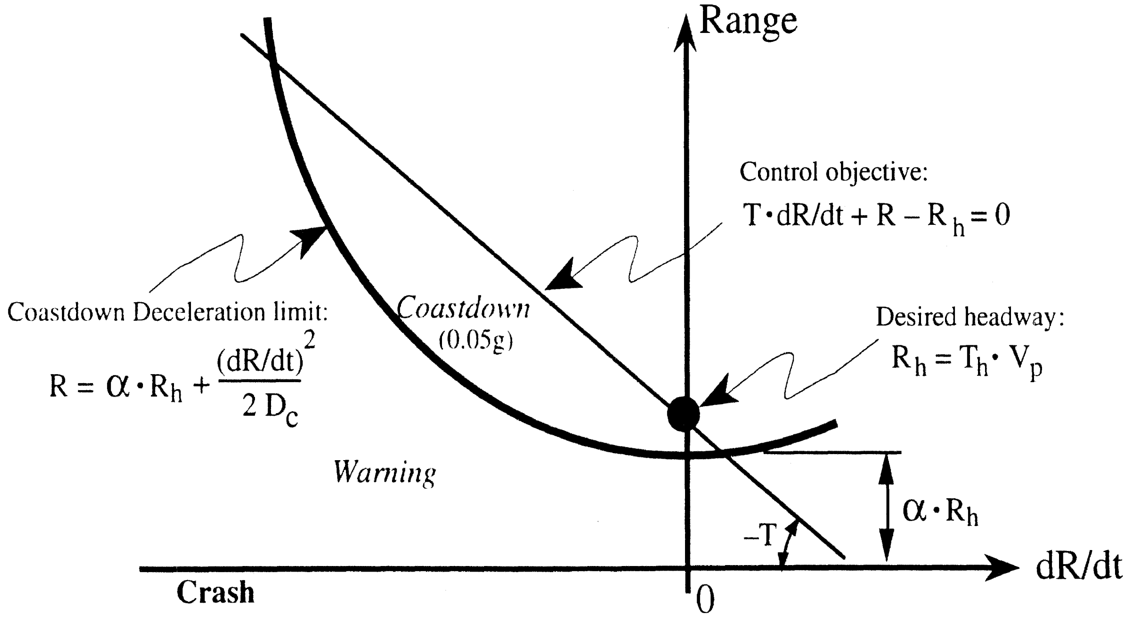


Figure 5.1 Audio Warning Design Principle

Given the range and range-rate information from the headway sensor, combined with the ACC-equipped vehicle's own velocity, the system can determine which of the "zones" depicted in Figure 5.1 is pertinent. If we are within the coastdown zone, the system can control the vehicle's speed by using only the throttle (and a maximum deceleration of 0.04g) to reach the desired headway without getting closer then $\alpha \cdot R_h$ to the preceding vehicle. On the other hand, if we are below the coastdown-deceleration parabola (and $dR/dt < 0$), then by using only the throttle we will not be able to reach the desired headway without getting closer than $\alpha \cdot R_h$ to the preceding vehicle. In this case a warning is issued to the driver.

5.2 Downshift Cue

ACC functionality was enhanced this year to expand the scope of headway conflicts that can be managed by the system. By incorporating a control signal for commanding transmission downshift, a higher level of deceleration was obtained, and the system was able to autonomously resolve situations that would otherwise (with throttle control only) have required driver intervention. At the same time, this abruptly-applied deceleration pulse provided a cue that was staged higher than that arising from throttle release at coastdown, thus more emphatically calling the driver's attention to the forward scene.

The downshift design, incorporated into the basic headway-control system and the warning cue that was described in the previous section, is illustrated in Figure 5.2. New design parameters in that figure are:

- D_s — maximum deceleration level when coasting down in downshift (0.07g).
- β — minimum fraction of the desired range.

Similar to α, the value of β is determined according to design preferences: it represents the shortest range for operation without a warning. Warning is issued if the system predicts, or if the data indicate, that the headway gap becomes shorter than $\beta \cdot R_h$. However, in this case, if the system predicts, or if the data indicate, that the headway gap becomes shorter than $\alpha \cdot R_h$ (but still larger than $\beta \cdot R_h$), the system will only downshift without issuing a warning. These design parameters have pre-set values that are part of the headway-control algorithm.

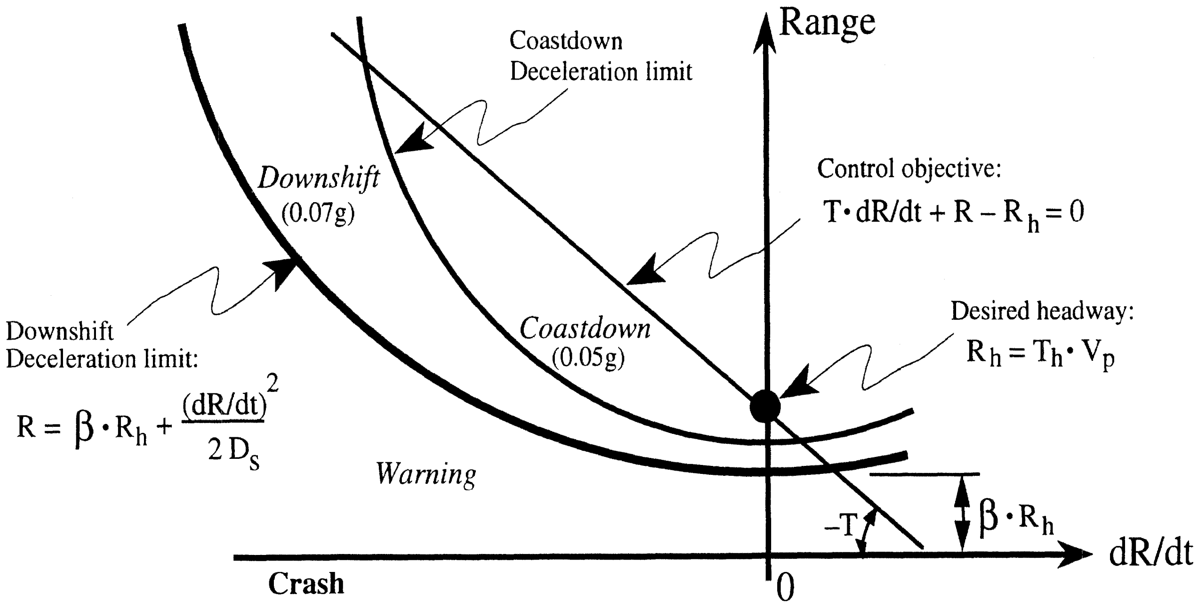


Figure 5.2 Downshift Design Principle.

When the system deduces that a developing headway conflict cannot be suitably resolved by means of throttle manipulation, it commands a single-gear downshift to the transmission. If the added deceleration cannot resolve the conflict, or if the associated low-decel cue did not result in driver's intervention, then the audio warning is issued to prompt the driver more urgently.

5.3. Brake Applicator Warning

Another stage (in the sequence of driver warning cues added this year) was achieved through a brake applicator device. The brake applicator was incorporated into the system's design so that it operated together with those warning cue elements described above. In addition, as a consequence of the OEM design of the cruise-control system in the vehicle, actuation of the brake applicator causes the ACC system to disengage.

In the context of crash-avoidance systems, the brake applicator that was devised this year serves as an initiatory system to foster the development and evaluation of full-time crash-avoidance systems. By employing a deceleration pulse that serves as a warning cue, together with initiating a significant speed reduction, some of the benefits and drawbacks of such active crash-avoidance systems could be evaluated.

When the system determines that it is necessary to slow down, it uses the throttle as the first means of deceleration control. By doing so, an approximate deceleration of up to 0.05g is achieved.

If the severity of the conflict calls for more than coastdown deceleration, the transmission is commanded to downshift, resulting in approximately 0.07g of deceleration. If by now the driver has not intervened and yet a still more aggressive response is needed, the audio warning is issued. Up to this point, the sequence of warning-cues is identical to that described in the previous section, and the operative state of the system is still that of ACC engagement. With the brake applicator in place, however, the system continues to evaluate the headway conflict and activates a braking pulse if the required level of deceleration is computed to be at 0.1g or higher. Consequently, a deceleration pulse of approximately 0.1g is obtained. The resultant abrupt-deceleration pulse serves as the fourth in the sequence of warning cues. The audio warning continues to be activated to further alert the driver. Using the range-range rate space, this sequence of staged warning cues is depicted in Figure 5.3.

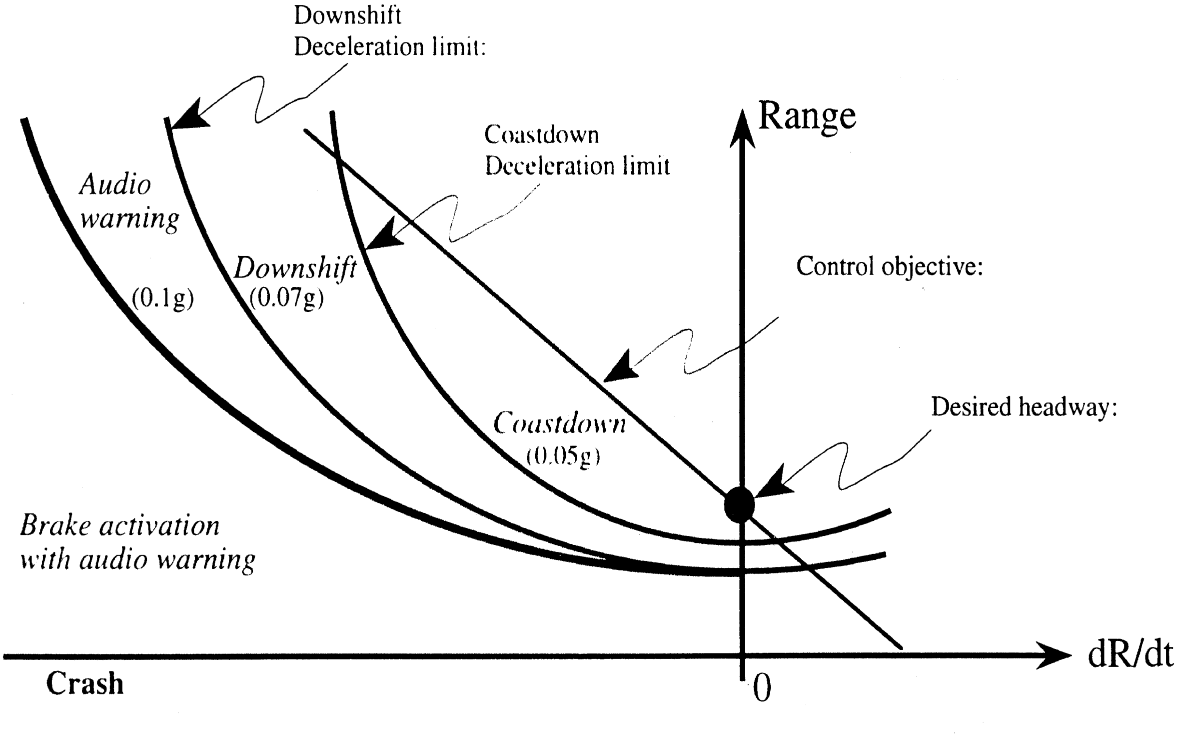


Figure 5.3 Brake Applicator Warning.

The brake applicator design implemented here involved electro-mechanical actuation of the pedal itself. (See Figure 5.4). This approach was taken because we did not have access to the OEM brake electronics system, and for safety reasons we wished to avoid any modification that might affect its operation.

As shown in the figure, a servo motor was installed next to the brake pedal, with a pulley on its shaft. A high-tensile ribbon was attached between the pulley and the bottom side of the brake pedal. To activate the brake applicator, an output signal from the headway-control unit commanded the servo motor to apply a prescribed level of torque on the pulley. As a result, the ribbon exerted a known force to the brake pedal, and the brakes were applied. By experimenting with the system, the torque output was calibrated to achieve the desired deceleration level (0.1g).

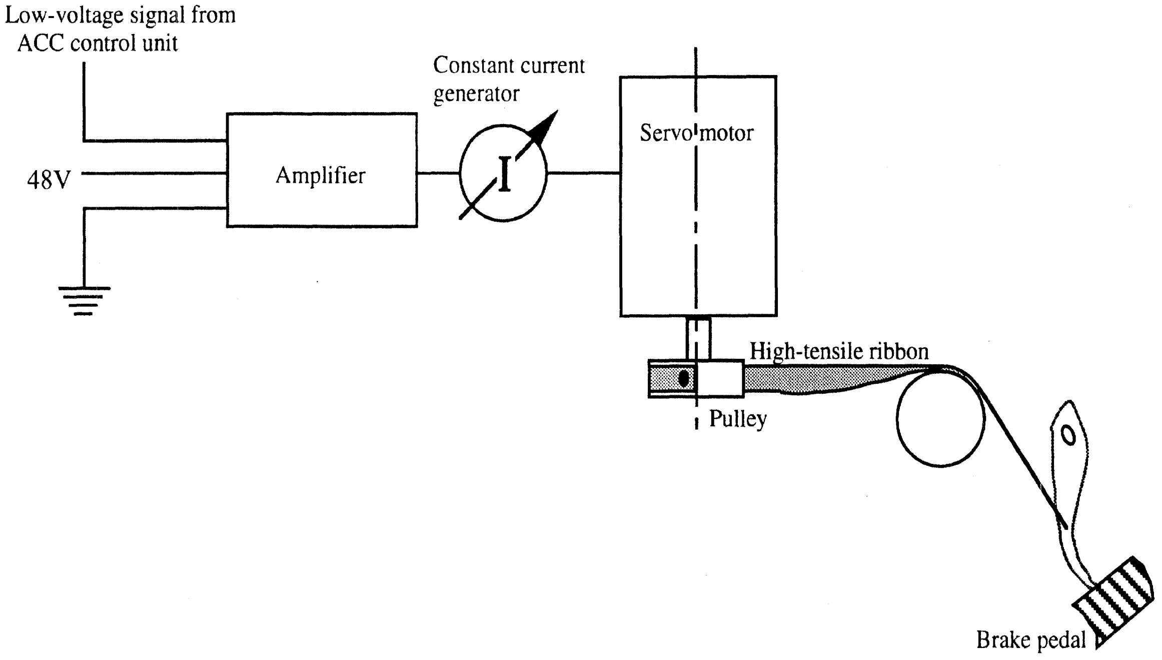


Figure 5.4 Brake Applicator Design.

Since the system in general, and the brake application in particular, were designed as a cueing mechanism rather than as a means for crash avoidance, the system does not automatically resume ACC operation following the braking pulse. The design concept applied in this work was based on the following principles:

- When the brake applicator is activated, it remains active (brake pressed) for only a prescribed period of time (1 sec);
- At the end of that time period, the brake activator is released regardless of the headway situation;
- In accordance with current design principles of OEM cruise-control systems, when the brakes are applied the ACC system disengages (it ceases to control speed);
- If the driver wishes to resume ACC operation, he/she must take action by pressing the appropriate button (commonly labeled "Resume").

6.0 Extending the Level of Control Authority

As a precursor to next year's activities, arrangements were made to drive a 1995 Volvo that is equipped with a Leica ODIN 4 sensor and electronic braking such that the ACC system has a control authority sufficient to apply 0.2 g if requested. The ODIN 4 employs a yaw rate gyro to aid in tracking vehicles on curves and avoiding false alarms due to vehicles in adjacent lanes. Although the control algorithm is proprietary to Leica, it was observed that large values of deceleration (greater than approximately 0.1g) were applied only in extreme situations.

The research personnel who have driven this vehicle find it to be a very pleasing ACC system. The steered-sensor-beam feature appears to be a considerable improvement over the fixed beam sensor, although the fixed beam has considerable utility for aiding the driver in controlling headway. The braking feature is important in aggressive, competitive traffic.

Both this Volvo and one of the FOT vehicles (a 1995 Chrysler Concorde with an ODIN 4 sensor [2]) were driven in relatively heavy traffic along the same section of I-696 passing through the northern suburbs of Detroit. The Volvo appeared to be clearly better to the driver. It seemed that the other drivers on the road were not concerned with the headway control performance of this ACC system. However, the FOT system characterized by zero braking authority and much less responsiveness to acceleration commands appeared to cause frustration to other drivers who were in a hurry. Nevertheless, the vehicle with less acceleration and deceleration capability was able to operate (function as designed) in crowded conditions. However, the more capable vehicle provided a much greater level of convenience and less stress than the less capable vehicle. Although this experience represents a very limited effort, it seems clear that drivers will tend to prefer ACC systems whose deceleration authority is in the 0.1 to 0.2 g range. Whether such systems will pose safety concerns with regard to over-reliance on the ACC system is an issue to be explored in future work.

7.0 Crash Avoidance in Addition to Convenience

This section has a philosophical tone because there is little operational experience or theory of driving to use in guiding decisions with regard to means for reducing the number and severity of crashes.

A useful construct for accident mitigation involves three dimensions. The first is the exposure to risky situations. ACC systems may contribute to eliminating risky situations by controlling headway times to less risky values than those associated with manual driving. The second dimension is concerned with reducing the probability of a crash given the presence of a risky situation. This dimension could involve use of the foundation brakes not only as a warning but also as a dynamic action to mitigate the likelihood of a crash. The third dimension involves reducing the severity of injury given a crash. In a sense ACC might apply to this dimension in that slowing the vehicle will tend to reduce the severity of the injuries if a crash were to ensue. This section focuses on safety concerns associated with the use of warning and braking features that go beyond those needed to provide the basic convenience and ease of ACC driving.

7.1 Operational considerations

At an operational level there seems to be difficulty separating comfort/convenience features from safety features. ACC systems as currently conceived by vehicle manufacturers are intended to provide comfort and convenience. With regard to comfort and convenience, the ACC systems as currently configured in the FOCAS work and the FOT program can make driving much easier for those drivers who are willing to let the ACC control headway. The driver will find that attentional workload is reduced, and hence, the psycho-physiological stress involved with controlling the throttle may be greatly reduced especially after several minutes of driving with ACC.

With regard to crashes, the convenience of ACC could be both good and bad. If the workload reduction provided by ACC were to be used for safety purposes, the number of crashes could be reduced. However, if the new attentional capacity is used to perform side tasks that were not ordinarily attempted by the driver, there could be a degradation in safety. There have been indications that drivers might dial their cellular phone while underway or glance occasionally at their baby in the back seat while driving with ACC engaged. Given the uncertainty as to how the driver might choose to react to the ease of ACC driving, one can postulate that there needs to be a means for keeping the driver informed or aware of the headway situation.

The relatively unsophisticated ACC system installed in the Saab 9000 appears to require a level of alertness to the scene ahead exceeding that needed simply to maintain vehicle path. There are two ways by which this ACC configuration seems to enhance the attentional state. First the system is a fixed beam system so the driver knows to be on the look-out for missed targets. (The idea of being on the look-out for missed targets is important with any remote sensing technologies currently available. Clearly some systems have fewer missed targets than others, but they all will miss on occasion.) The number of missed targets seems to be small enough for the ACC system on the Saab so that drivers do not get disgusted and, in addition, they seem to learn what to expect so they are seldom surprised. Furthermore, ACC-controlled speed changes on this system are accompanied with enough jerk that the driver's attention is immediately drawn to the forward scene. In this manner, the ACC system has a way of getting the driver's attention. Although longitudinal jerk can be perceived as uncomfortable, it seems that the level of jerk in the Saab is about right with regard to getting attention with minimal nuisance. Perhaps the principle is that the driver does not form a negative impression if the applied deceleration cue appears to be warranted by the conflict ahead.

Drivers are very sensitive to small, quick changes in deceleration and velocity. This is fortunate for drivers that are supervising the performance of the ACC system installed in the vehicle they are driving. When the ACC system in the Saab slows the vehicle, the driver is warned that there is a conflict to be resolved. For systems that are very smooth and whose levels of deceleration authority are insufficient for managing large values of closing range-rate, a warning such as an intentional sudden change or initiation of deceleration could be added. The following material discusses how performance measures called "time to impact" and "deceleration demand" could be used to prompt crash avoidance warnings.

7.2 Time To Impact And Deceleration-Demand Lines

If the ACC system tends to slow the vehicle much earlier than seems necessary, drivers will complain. They will find premature slowdown to be distracting, and it can even interfere with passing maneuvers if the vehicle starts to slow just before the driver pulls out to pass. Nevertheless, if the closing rate happens to be large due to a slow moving vehicle ahead, the ACC with modest control authority may need to start slowing down the vehicle at relatively long range. Even if the ACC does not have enough control authority to prevent a crash, it could be designed to call the driver's attention to the existence of a potential problem ahead.

The "time to impact" ($TTI = R/-Rdot$ for $Rdot<0$) is a measure that is a candidate for use in warning the driver. The idea would be to apply a lo-decel cue, such as that described in Section 5. The lo-decel cue would be applied when time to impact is less than 10 seconds, for example. In the range versus range-rate space, lines of constant time to impact are straight lines, as illustrated in the velocity-normalized diagram shown in Figure 7.1.

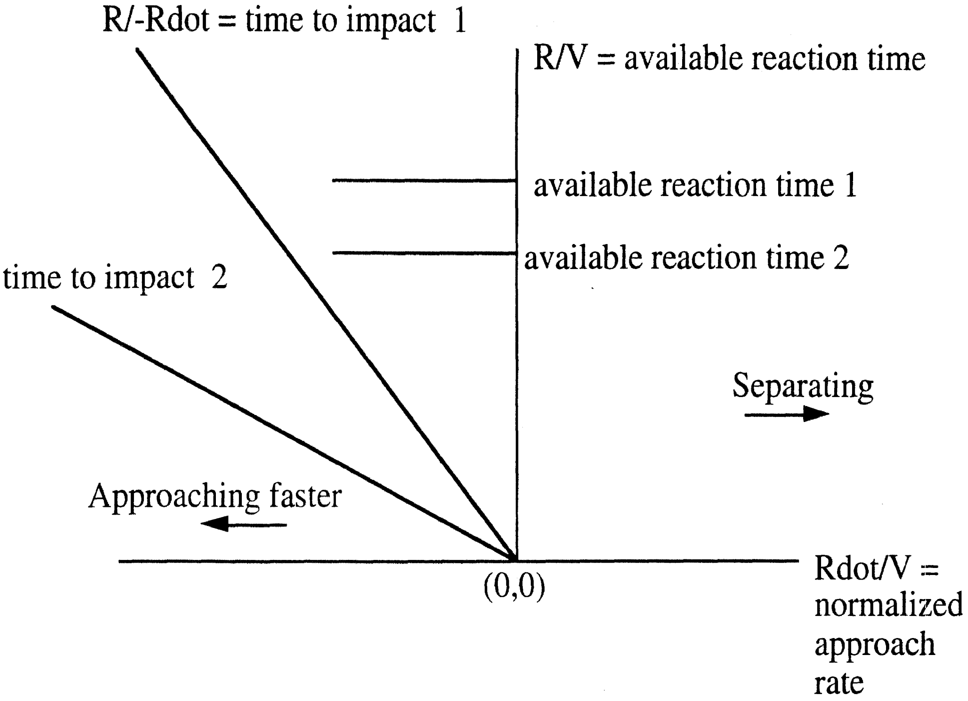


Figure 7.1 Lines of Constant Time to Impact in a Normalized Range vs. Range-Rate Space.

As mentioned previously in connection with Figure 3.2, times to impact for manual driving are usually greater than 10 seconds. Values less than 10 seconds do occur, but only infrequently. A warning issued when headway time is less than 10 seconds appears to be a good choice that will provide enough time for the driver time to respond as well as having a non-aggravating frequency of occurrence. Operational testing is needed to support or refute this choice.

There is another measure that could be used for issuing a warning. This is the deceleration demand needed to avoid a crash. Lines of constant deceleration demand are parabolas in the range versus range-rate space. (See Section 5.) These parabolas are determined by two parameters: the range intercept at Rdot equal zero and the level of deceleration chosen. The equation for a constant deceleration line is:

$$R = Ri + (Rdot)^2 / 2\ Dc \qquad (7.1)$$

where,

Ri is the intercept and Dc is the chosen deceleration level.

For a crash warning boundary, Ri might be set to zero or some small range, perhaps approximately one car length. The level of deceleration might be chosen to be a fairly infrequent level for highway driving (0.1 g for example) but close to the deceleration authority of the ACC system. For the types of ACC system capabilities considered in the FOCAS project and the levels of deceleration employed in manual driving on freeways, Dc = 0.1g appears to be a reasonable choice for defining a deceleration demand curve. As in the situation for time to impact, operational testing is needed to support or refute this choice.

There are practical considerations involved in favoring a time-to-impact or a deceleration-demand criteria for issuing a warning. The deceleration-demand parabolas curve upward such that warnings would be issued at fairly long ranges. At these long ranges drivers have a considerable amount of time before a crash is imminent. If the warning comes too soon the driver will tend to think that the system does not function properly and the driver is likely to feel dissatisfied with the system. Although the constant deceleration lines are dynamics lines, in the sense that they are the range versus range-rate trajectory for the chosen deceleration level, the time-to-impact lines represent the time to crash along a trajectory, with Rdot held constant at its current value. Analysis shows that, at each point on a constant deceleration-demand trajectory, it takes twice as long (while decelerating at that constant value) to reach a crash as that determined by the time-to-impact value for the same point. Although either a time-to-impact or a deceleration-demand criteria could probably be made to work, the time-to-impact criteria appears to be simpler to use and would seem to result in fewer unexpected warnings at long range.

Perhaps a logical combination of constant deceleration, time-to-impact, and maximum range criteria could be used to provide boundaries for the region in which warnings would be issued. See Figure 7.2. In this case the logical expression for when a warning is to be issued is as follows:

$$\begin{aligned} \text{Warn} = \text{true} \quad \text{when} \quad & ((R < Ri + Rdot^2/2Dc) \\ & \textit{and} \\ & (R < -\,10\ Rdot) \\ & \textit{and} \\ & (R < Rmax) \text{ is true}) \end{aligned} \tag{7.2}$$

otherwise,

$$\text{Warn} = \text{false};$$

Rmax is the maximum range at which a warning is to be given.

Clearly, many other logical expressions could be devised to develop warning boundaries based upon properties chosen for a particular design goal.

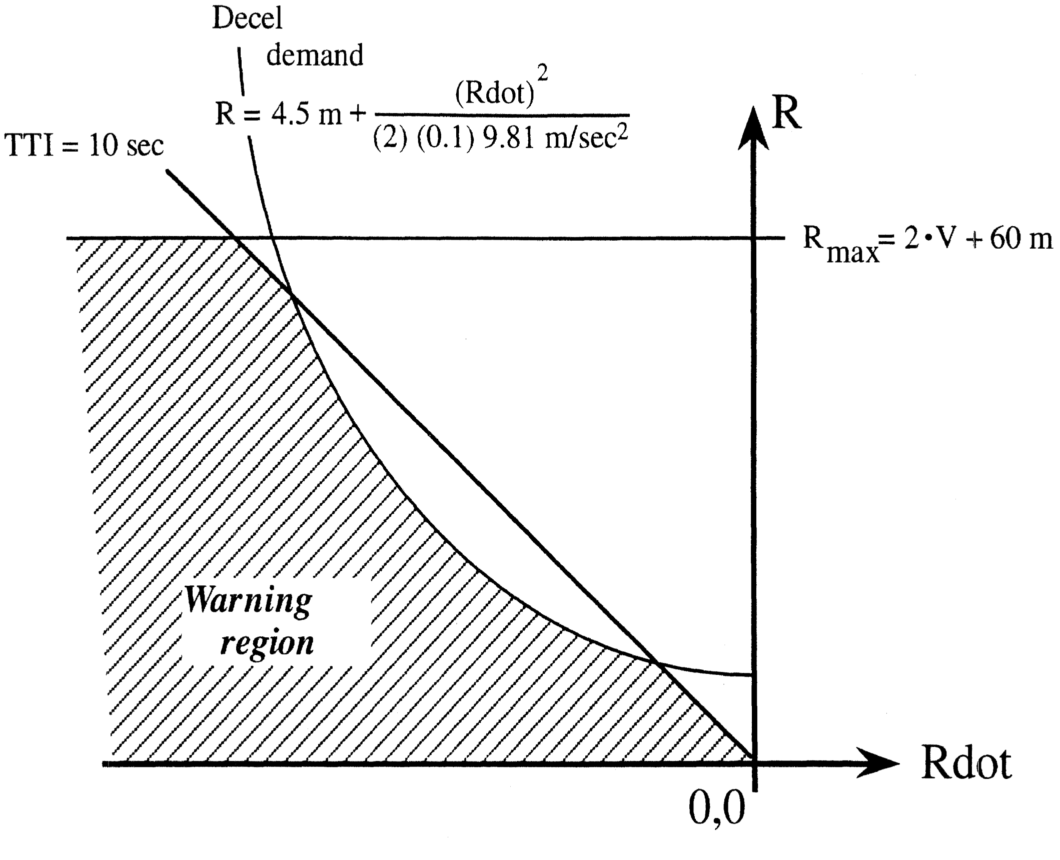


Figure 7.2 Example Warning Criteria.

7.3 Braking In Response To False Alarms

A primary consideration associated with the use of braking is the maximum level of braking allowed (the control authority of the system). Drivers in heavy traffic and close following situations depend upon preceding vehicles to maintain fairly constant speed. Sudden, unexpectedly large amounts of braking are dangerous and unacceptable in these situations. If the sensor were to provide a false alarm that caused braking for no reason that is apparent to the other drivers on the road, that would contribute to an undesirable situation that might lead to a crash. This means that sensor capability to avoid false alarms has a bearing on the level of deceleration authority of the system. Since all sensors have the potential to produce false alarms, the magnitude of the control authority of the ACC system is seen as a potential safety-related design issue. The systems being considered in the FOCAS project are aimed at trying to find a suitable compromise between the level of deceleration needed to provide a convenient ACC system and the amount of control activity that is acceptable in heavy traffic.

(Although the work has not proceeded this far, thought could be given to sensing the current driving situation and determining the appropriate conditions for turning all control over to the driver. In a sense, the ACC could at times turn complete control over to the driver because the system defers to human intelligence rather than trying to use its limited intelligence to resolve the current driving situation.)

Based upon our observations, the FOCAS project is aimed at deceleration authorities in the range from 0.1 to 0.2 g.

7.4 Dangers Posed by Stopped Objects And Driver Expectations Arising from High Levels of Deceleration Authority

The ideas presented in this subsection are speculative in the sense that we have very limited experience with deceleration levels greater than 0.05 g during ACC driving. However, all of our experience is with ACC systems that do not respond to stationary objects. A rule that we have commonly used is that the ACC system operates on preceding vehicles that are travelling at a velocity that is greater than 0.3 times our velocity. In this way there are few false alarms due to pavement dips and humps, as well as signs, bridges, trees, and other roadway features. Also, since the control authority is limited, the driver learns to take charge of the vehicle when slow moving or stopped vehicles are likely to be present.

The questions that our experience prompts are: What level of deceleration authority is compatible with the driver's ability to supervise the use of the ACC system? Will higher levels of deceleration (up to 0.2 g) pose a problem for the driver with regard to deciding to intervene by braking the vehicle? Will the driver tend to wait longer than that typical of manual driving? How does the level of deceleration authority influence the driver's ability to intervene with minimum delay?

There have been simulator studies that indicate that pathological situations involving stopped vehicles can be difficult to supervise [4]. The simulator test situations have been set up such that some small percentage of driver subjects fail to successfully avoid a crash during manual driving. The stopped vehicles come into view with little time to react. Results indicate that ACC drivers will be even less likely to prevent a crash than manual operators if they have been using an ACC system with 0.3 g of control authority. We do not know of results for lesser amounts of control authority. We also do not know the reliability with which these simulator results can be transferred to real driving situations. Nevertheless, it appears that it is reasonable for the FOCAS project to proceed to implement deceleration authorities that are considerably less than 0.3 g.

8.0 Concluding Statements

8.1 Summary Of Findings

The findings of the first two years indicate that ACC systems with limited deceleration authority (0.05 g) can provide a level of headway control that is both useful and desired by many drivers.

When controlling headway manually, drivers tend to follow preceding vehicles at closer range and to close-in more rapidly than they do when the ACC system is in operation under similar road conditions. However, this is because the ACC system imposes a fixed minimum value for headway time. The study of adjustable headway in an ACC system indicates that, if given the capability to do so, drivers will tend to set headways that are comparable to those they use when driving manually. The experiments done in this study allowed drivers to select headway times down to a minimum of 0.7 seconds. The results of testing show that many drivers would choose this minimum, and hence we believe that some drivers would have chosen values less than 0.7 seconds if the experimental set-up would have allowed it.

There are differences between the choices of headway time made by drivers from various age groups. The younger drivers tend to like short headways, while the older drivers are not inclined to choose headways less than 1.4 seconds. The evidence supports the conclusion that an adjustable headway feature is needed so that different drivers can personally select a headway time that they feel is compatible with the existing road and traffic conditions.

With regard to setting minimum and maximum headway times to constrain the range of headways for ACC systems, data for 36 subjects driving manually on freeways were analyzed to determine driving style with respect to average range-rate (relative velocity) and to the most likely value of the headway time chosen by the driver. Those that chose to travel at relatively high levels of closing velocity and small headway times were named "hunters," and those that chose to travel slower than the surrounding vehicles and at relatively large headway times were called "gliders." The drivers whose choices fell in between these two groups were called "followers" because they tended to travel at speeds and range distances that put them in the neighborhood of the general flow of the traffic stream.

A range of headway times from 1.0 to 2.0 seconds was found to be approximately typical of those drivers that are content to go with the flow of surrounding traffic. The fixed ACC system used in the first year had a headway time setting of 1.4 seconds, which is very close to the middle of the follower characteristics. Our more recent analysis of results covering hunters, gliders, and followers reconfirms the original choice of 1.4 seconds as a headway time setting that many drivers will find acceptable. Nevertheless, hunters (who are mainly younger drivers) will tend to feel that 1.4 seconds is too long for dense traffic conditions and gliders (who are mainly middle aged and older drivers) will generally prefer longer headway times. The range of headway time adjustment from 1 to 2 seconds represents a compromise that appears to be satisfactory to a wide range of drivers. The current field operational testing of ACC uses this range.

Selection of the allowable range of headway time is a design issue for future ACC systems. On the one hand, it seems logical that longer headway distances enhance the margin for safety, given the delay in typical driver reaction to abrupt conflicts in headway. On the other hand, our data indicate that many drivers do not seek such margins when they are driving. Thus, there is a tension between the desire to please the customer by accommodating short headway and concern for the associated safety hazards. A minimum value of 1.0 second for ACC headway time, for example, may well provide a safety benefit because it would provide a greater headway safety margin than that used by many drivers driving manually. And, of course, neither manual driving nor ACC could be expected to handle the worst-case driving scenarios.

An evolutionary approach would mean that ACC is a step towards an emergency automatic crash avoidance system but that will not be the primary capability of first-coming ACC products. ACC should, nevertheless, tend to reduce the level of exposure to potentially risky, close-following situations.

With regard to analyzing data from ACC operation, there are needs to look at individual incidents and situations as well as the broader statistical and frequency or probability implications of the data. Although various scenarios related to ACC operation seem relatively easy to conceptualize and define precisely, it is by no means as easy to find examples of these scenarios in the data. During the first year, rule-based definitions of driving scenarios were employed with only limited success at finding so-called "streams" of data (time segments capturing a stereotypical form of conflict). Example scenarios included following at constant speed, sudden merges into the path of the ACC vehicle, sudden slowdown by the preceding vehicle, closing in from long range, etc. In order to aid in automating the capture process for large sets of data, a neural network approach was developed and tried. Example results have been successfully produced. They show that the approach has promise, but is still in the research phase. Results to date show that the neural net identifies scenarios correctly in approximately 80 or 90 percent of the cases. Even at its present state of development the neural net approach can be used as a quick way to find samples of particular driving scenarios. It is not clear, however, whether the accuracy of identification would be adequate for directly counting different types of conflicts or driving scenarios in order to express the frequency/probability of their occurrence.

This year's work has also included the development of an audio warning based upon using range and range-rate data to compute the deceleration needed to meet a selected headway goal. As an example, the warning system could use a headway distance of 0.5 times the desired headway employed in the controller and a deceleration level of 0.05 g to establish a warning boundary. By such an arrangement the driver would be prompted to intervene whenever the pending headway conflict is computed to be more severe than can be managed by the ACC system. Clearly the values chosen for the warning criteria depend upon the characteristics of the particular ACC system. Nevertheless, the concept of using a deceleration parabola as the warning boundary, as demonstrated this year, is believed to have fundamental merit.

Another type of warning, as well as an extension of the control authority of the ACC, was provided by downshifting the transmission when a deceleration greater than that of coastdown was required. In this case a constant deceleration parabola was also used as a boundary. When the measured range falls below this parabola, the transmission will downshift. The additional deceleration provided by the downshift not only slows the vehicle more rapidly but it also provides a deceleration cue to the driver. The choice of parameters in deceleration parabolas for the audio warning and the downshift function can be chosen to ensure that downshift precedes audio warning. In this manner the driver receives a two-stage cue indicating the need for additional deceleration.

An additional warning system called a "lo-decel-cue" was also studied this year. This system used the foundation brakes, though only in a constrained manner, to warn the driver. The idea is to apply a limited level of brake pedal actuation corresponding to approximately 0.1 g of deceleration, for example. This braking is applied for a short period of time and also causes the ACC controller to disengage. In response to this type of cue, the driver must resume manual control of the vehicle deciding whether to later re-engage the ACC or to continue driving manually. The brake-induced cue is seen as a third and final stage of warning and thus comes after downshift and audio warnings have occurred.

Limited experience operating an ACC system having approximately 0.18 g of controlled braking capability was also obtained during year two. Preliminary evaluation of this system indicates that the additional control authority due to braking adds to the comfort and convenience of ACC especially when operating in fairly dense traffic that approaches the capacity of the freeway.

The second year effort has added understanding and improved methods for studying higher-level functionalities in the third year. Major issues remain in transitioning from ACC as a comfort and convenience system to systems that provide a certain level of crash warning and even crash avoidance capability for reacting to hazards that develop in the forward view.

Sections 8.2 and 8.3 provide insights concerning next year's research work.

8.2 Implications Of The Findings With Regard To 3rd Year Work

Table 8.1 contains a list of attributes derived from the experience obtained in the first two years of the FOCAS project. In a sense these attributes represent issues that might be further developed and studied by the end of the third year. Many of the attributes are expressed in qualitative terms such as "suitable" or "satisfactory." Where possible, replacing those qualitative terms with quantitative measures is a worthy goal.

Table 8.1 Attributes for Longitudinal/Headway Control

An ACC system should:

1. be able to close-in on a slower moving vehicle in a manner that allows following at a suitable headway (Rh) and speed ($V = Vp$).
2. be able to close-in on a slower moving vehicle in a manner that allows the opportunity to pass efficiently with $V > Vp + \Delta V$ and $R > Rh$.
3. if a vehicle merges or cuts-in to the headway gap, be able to re-establish a suitable headway; detect cut-ins "early" (as soon as possible after the lane of travel is penetrated).
4. if the lead vehicle slows-down to adjust its speed ($Axp > -0.05$ g), be able to maintain headway.
5. if the preceding vehicle speeds-up to adjust its speed ($Axp < 0.05$ g), be able to maintain headway up to the ACC driver's chosen set speed.
6. if there are no moving vehicles (detected targets) in the path of the ACC vehicle, travel at the set speed.
7. if the preceding vehicle decelerates, respond in a way that preserves the driver's sense of responsibility and timing for manual brake intervention. (The system should try to make the intervention task as easy and reliably-executed as possible for the driver.)
8. if a stopped or slowly moving object is encountered, respond in a way that preserves the driver's sense of responsibility and timing for manual brake intervention. (The system should try to make the intervention task as easy and reliably-executed as possible for the driver.)
9. do not jerk the driver (or the passengers) unacceptably in the process of control modulation, particularly in the scenarios associated with items 1 through 6 above.
10. maintain satisfactory available reaction time (R/V) for sudden changes in the speed of the preceding vehicle.
11. maintain suitable time to impact. ($tti = R/\text{-}Rdot$ for $Rdot < 0$)
12. maintain suitable deceleration demand to avoid a crash. ($dd = Rdot^2/2R$, $Rdot < 0$)
13. limit errors due to missed targets to situations readily identifiable and correctable by the driver. (Do not accelerate aggressively during brief "miss" episodes.)
    - 13.1 restrict the frequency of missed targets to a very small value.
14. limit the system's response to false target detection errors to benign levels of deceleration. (Do not make a rapid stop in heavy, high speed traffic when there is no apparent danger.)
    - 14.1 restrict the frequency of missed target detections to a very small value.

15. if the road ahead clears up, be able to accelerate to the set speed in a timely manner. (Do not leave the vehicle in the passing lane going slowly with little acceleration.)
16. put-on the brake lights if the system causes $Ax < -0.05$ g.
17. warn the driver if items 11 or 12 are not maintained.
18. warn the driver if visibility is poor or sensor performance is excessively degraded due to dirt, weather, contamination, breakage, or failure. (Shut down the ACC.)
19. keep the driver informed as to the current set speed and whether a target is detected.
20. make it easy for the driver to adjust set speed (even when operating in headway mode).
21. make it easy for the driver to adjust desired headway over a suitable range of headway times or distances.
22. render an intuitively understandable system function such that the driver's expectations of system response are rarely incorrect. (Avoid placing the driver in confusing or unsafe situations.)
23. to the extent possible, relieve the driver from the need to control the accelerator pedal, brake pedal, and/or cruise control buttons, especially with regard to routine speed adjustment. (Allow the driver more time to concentrate on other driving tasks.)
24. discriminate a relatively small target behind a relatively large target, such as the case of motorcycles following close behind large trucks.
25. maintain headway without excessive range variation.
26. sustain ACC engagement as long as atmospheric conditions allow a level of human visual acuity that is sufficient for full driver supervision of the ACC function (covering the normal minimums for safety-vigilance).
27. track targets in the lane of travel for curve radii covering the range encountered on U.S. highways. (1000 feet and greater, for example.)
28. operate within the same speed range as standard cruise control.
29. restrict the frequency of system dropouts to a very small value.
30. limit the need for sensor calibration and alignment.
31. do not respond to vehicles travelling in other lanes or to the detection of any other objects whose presence is inconsequential to safe operation with ACC engaged. (such as roadside leaves oscillating in the breeze).
32. make it readily apparent when driver intervention is needed.

The list of attributes given in Table 8.1 is long and to a certain extent it contains redundancies. This compilation of requirements reveals that the number of factors that are pertinent to ACC operation is large and that their descriptions are often subtle — challenging our understanding of the driving process.

The chart given in Figure 8.1 provides an assessment of current perspectives on basic issues pertaining to the attributes and development of ACC systems. The entries in the chart are based upon qualitative assessments of the effectiveness of the systems we have used.

Attributes, longitudinal control ↓	**driver &tech** → sense	perceive	decide	act
1. close-in on a slower moving vehicle & follow it	G/t	G/t	G/t	G/t
2. close-in on a slower moving vehicle & pass it	G/t	G/t	P/d	P/d
3. respond to merges and re-establish headway	M/t	G/t	G/t	M/t
4. respond to a lead vehicle's speed adjustments	G/t	G/t	G/t	M/t
5. travel at a chosen set speed when the path is clear	G/t	G/t	E/t	M/t
6. be ready to stop for fixed or slowly moving objects	P/d	M/d	M/d	G/d
7. do not jerk the driver or passengers	G/t	G/t	G/t	G/t
8. maintain suitable reaction, impact, and decel times	G/t	G/t	G/t	M/t
9. limit the impact of missed & false targets	M/d	M/d	M/d	G/d
10. provide intervention cues to the driver	M/t	M/t	G/t	M/t
11. relieve the driver from having to adjust speed manually	G/t	G/t	G/t	G/t
12. provide understanding of limitations (weather, traffic, etc.)	P/t	P/t	P/t	P/t

key to entries: E-excellent, G-good, M-mediocre, P-poor, B-bad, N-nothing

E or G —no problem, M or P —can move ahead, B or N —show stopper

t —based on technology, d —based on driver's skill

Figure 8.1 Qualitative Ratings Concerning ACC Attributes.

These assessments are difficult to make because the driver and the ACC technology are operating together so there is a judgment involving whether the driver can handle the situation if the technology does not. That being the case, the chart may have more value as an illustration of the complex performance issues posed by a man-machine system of this type than as a definitive assessment of the actual situation with ACC per se. At this point, Figure 8.1 serves as a condensed assessment of prototype and early ACC systems with respect to many of the attributes listed in Table 8.1.

In Table 8.1 the assessment of driving performance is broken down into four areas labeled: "sense," "perceive," "decide," and "act." These are the elements of how an "intelligent" system performs its tasks. The entries in Figure 8.1 indicate how well the man-machine system performs each step in its intelligence function. There is the notion here that the ACC system performance will be constrained by the weakest element (sensing, perceiving, deciding, or acting) in each functional attribute.

The work planned for next year will address the following items pertaining to the factors included in Table 8.1 or Figure 8.1:

- enhanced ability to act with more authority by including braking as a means to provide greater deceleration authority for following and responding to deceleration of the preceding vehicle.
- enhanced ability to operate on curved paths, thereby limiting the number of false alarms and missed targets.
- warning systems that are included to raise the situation awareness of the driver when time to impact, deceleration margin, or reaction-time margin become small.
- the smoothness of system operation when braking is employed (jerk level).
- greater utility by reducing the number of situations in which manual intervention is necessary.

8.3 Expectations For The 3rd Year

The technology-related work for the third year will focus primarily upon the addition of braking to the ACC system. We plan to incorporate braking technology into an ACC system installed in a 1996 Chrysler Concorde. We expect the vehicle to be equipped with a Leica ODIN 4 sensor and a smart brake booster system provided by ITT. (These arrangements are currently under negotiation with ADC (a Leica and Temic joint venture) and ITT.)

The control of headway will be achieved through the use of both the throttle and brake controls installed on the Chrysler Concorde. Figure 8.2 shows the architecture for this control system.

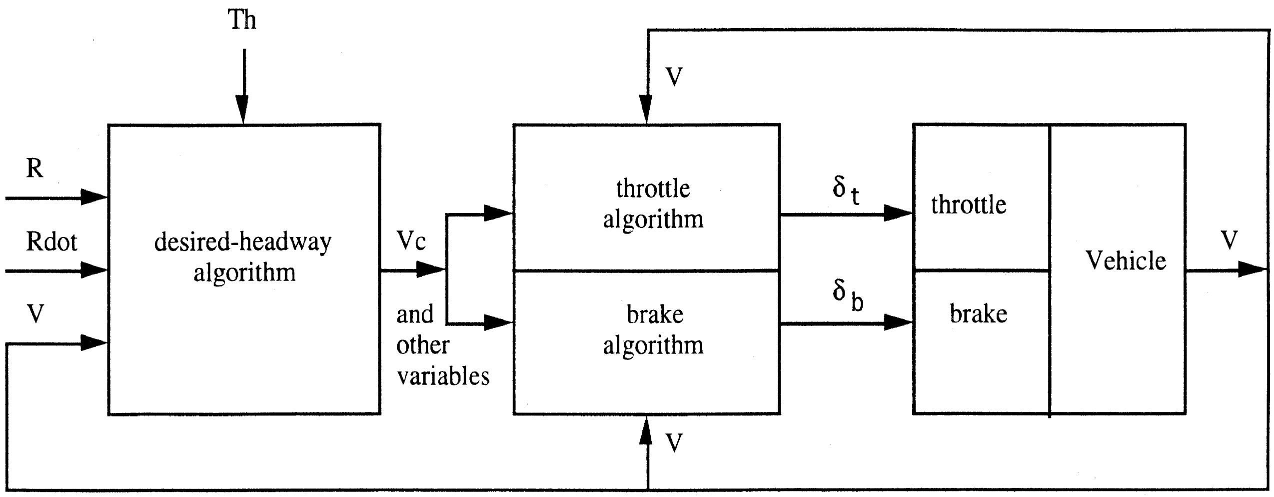


Figure 8.2 Control Architecture of the ACC System Planned for the Third Year.

The figure incorporates goal-related inputs to the control system from the sensor's range and range-rate signals. The velocity of the ACC-equipped vehicle serves as the feedback signal used in an outer control loop and in two inner loops: one inner loop for throttle actuation and the other inner loop for brake actuation.

The control functions of the outer loop and the throttle-related inner loop are very similar in nature and concept to those of their counterparts in the original ACC system. The new aspect of this ACC system is the braking inner loop. The basis for the braking control algorithm that we have created will be explained in the context of our overall ACC system concept.

The control concept is based upon an overall goal for the ACC system. This goal is expressed in terms of the sensor outputs R and Rdot and the velocity feedback V; viz.,

$$T\ Rdot + R - Rh = 0$$

$$\text{where, } Rh = (V + Rdot)\ Th \text{ and where } V + Rdot = Vp \qquad (8.1)$$

T is a time constant for setting the speed of response,

Th is the driver set headway time,

and Vp is the speed of the preceding vehicle.

In order to better explain the control idea, its basic generalized form is illustrated in Figure 8.3. The outer loop (which includes the inner loop as a special actuation loop) involves a "planner" element that looks at the sensed information, including the velocity of the vehicle and the external quantities R and Rdot and decides what "command" to give to the "controller." The controller uses this command to generate control signals that cause the vehicle to respond in a manner that is consistent with the goal.

Specifically for this ACC system, the planner uses measured information about R, Rdot, and V in conjunction with the goal expressed by equation 8.1 to generate a commanded velocity Vc. Clearly the difference between Vc and V is the error expressed in terms of velocities. Now consider the following set of equations:

$$Vc - V = \text{the "error"} = Rdot + (R - Rh)/T$$

The function of the planner is expressed implicitly by the equations above. Explicitly the planner tells the controller what to do using the following equation.

$$Vc = Vp + (R - Rh)/T \qquad (8.2)$$

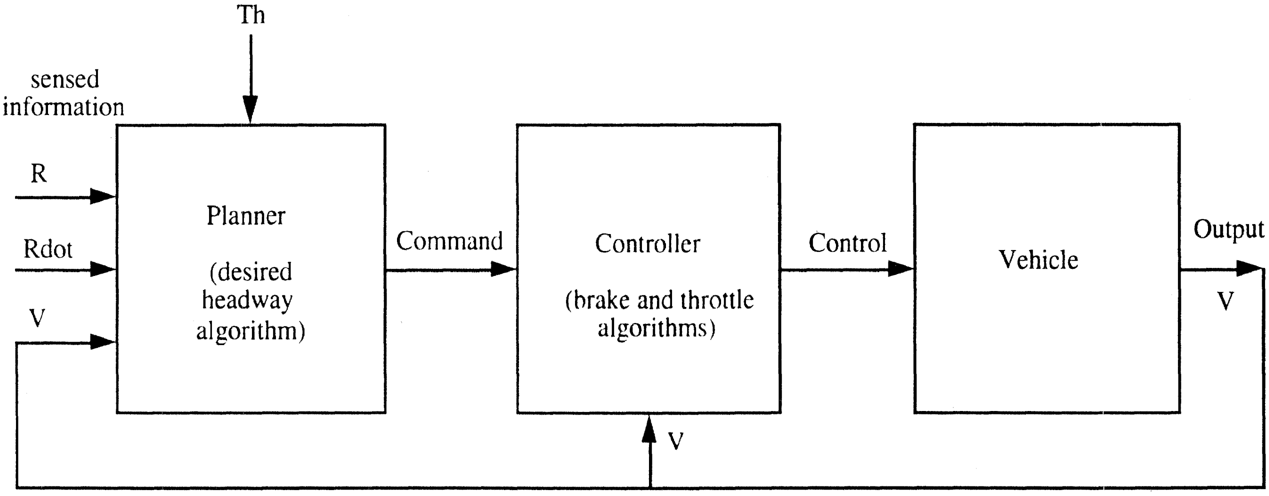


Figure 8.3 Control Architecture Based on a Goal-Oriented Planner.

Equation 8.2 makes physical sense. For the ACC-equipped vehicle to be following the preceding vehicle properly, it needs to be going the same speed as the preceding vehicle and at a range R equal to the desired-range Rh. This fits the notion of having a planner that is, in effect, a decision maker.

The throttle control is one half of the controller package indicated in Figure 8.3. In the prototype systems used in FOCAS the vehicle's conventional cruise control is modified to accept velocity commands (Vc) from the planner. The modified cruise control has been shown to perform the controller function well enough to provide a usable level of ACC performance. This means that the throttle is modulated to bring V to match Vc with adequate fidelity and responsiveness.

(Better performance might be obtained by redesigning the cruise control, but we do not have access to the Chrysler engine controller. We must use this part of the system as a black box that we cannot change. However, while the modified cruise control may not be excellent, it is adequate for causing V to eventually approximate Vc and thereby to satisfy the goal expressed by equation 8.1, approximately.)

Now consider the controller for braking. In this case we have the opportunity to design the controller to suit. Our design is created from three equations expressing three considerations pertaining to (1) the dynamic properties of the vehicle, (2) the nature of the smart booster for actuating the brakes, and (3) the desired performance of the controller. For control purposes, the following three equations pertain to each of the three considerations respectively:

m Vdot = - Fdrag - Fbrake (8.4)

where, m is the mass of the vehicle,

Fdrag is the coastdown deceleration of the vehicle (approximately 0.02 g), and

Fbrake is the braking force produced by the smart booster/brake combination.

Fbrake = Kb δb (8.5)

where, Kb is the gain of the smart booster / brake system and,

δb is the controlled master cylinder displacement within the smart booster.

(It is believed that the booster/brake combination will be much faster than the requirements of the outer loop and that it can be approximated roughly by a linear gain. If not, a more complicated, possibly nonlinear function can be used, but the idea behind the controller design process is the same.)

(Tb) edot + e = 0 (8.6)

where e = Vc -V , and
Tb is 1/10 of the time constant for the system goal expressed in equation 8.1, i.e. Tb = T/10.
(The dynamics for the controller are chosen to be a first order system that is approximately 10 times faster than the dynamics of the goal.)

Upon solving equations 8.4 through 8.6 simultaneously and noting that Vcdot is small because Vc will change slowly compared to dt, the following equation is obtained for the brake controller:

$$\delta b = (m/Kb) \{[(10/t)(Vc - V)] - Fdrag/m\} \quad (8.7)$$

where, $Fdrag/m = 0.02$ g.

The point is that the basic design of the brake controller is easy to accomplish once the vehicle and the control actuator are well understood. If the vehicle or booster/brake combination are nonlinear, the process is known as "feedback linearization," but the process of solving for the control is still one of solving simultaneous equations. This is also the first step towards a sliding mode control; however, for this application we do not want or need the abruptness of the sliding mode functionality. Furthermore, we will limit the amount of braking authority that the ACC system will have. In a sense, the controller will be somewhat like a modified sliding mode control with a boundary layer. Nevertheless the architecture of the controller is straightforward.

There will be detail issues to resolve pertaining to items such as keeping the brakes and engine from fighting each other, but they are naturally separated by the amount of drag. Fdrag, in this preliminary design, is represented by 0.02 g, which is expected to be adequate for not applying the brakes too soon.

There are also issues involving the rules as to how and when the limits on braking and acceleration authority will be accomplished. We have developed a simulation capability to aid in resolving these details of the design, but we expect to obtain support from ITT and ADC and NHTSA so that we can implement these ideas in an operating prototype in the next year.

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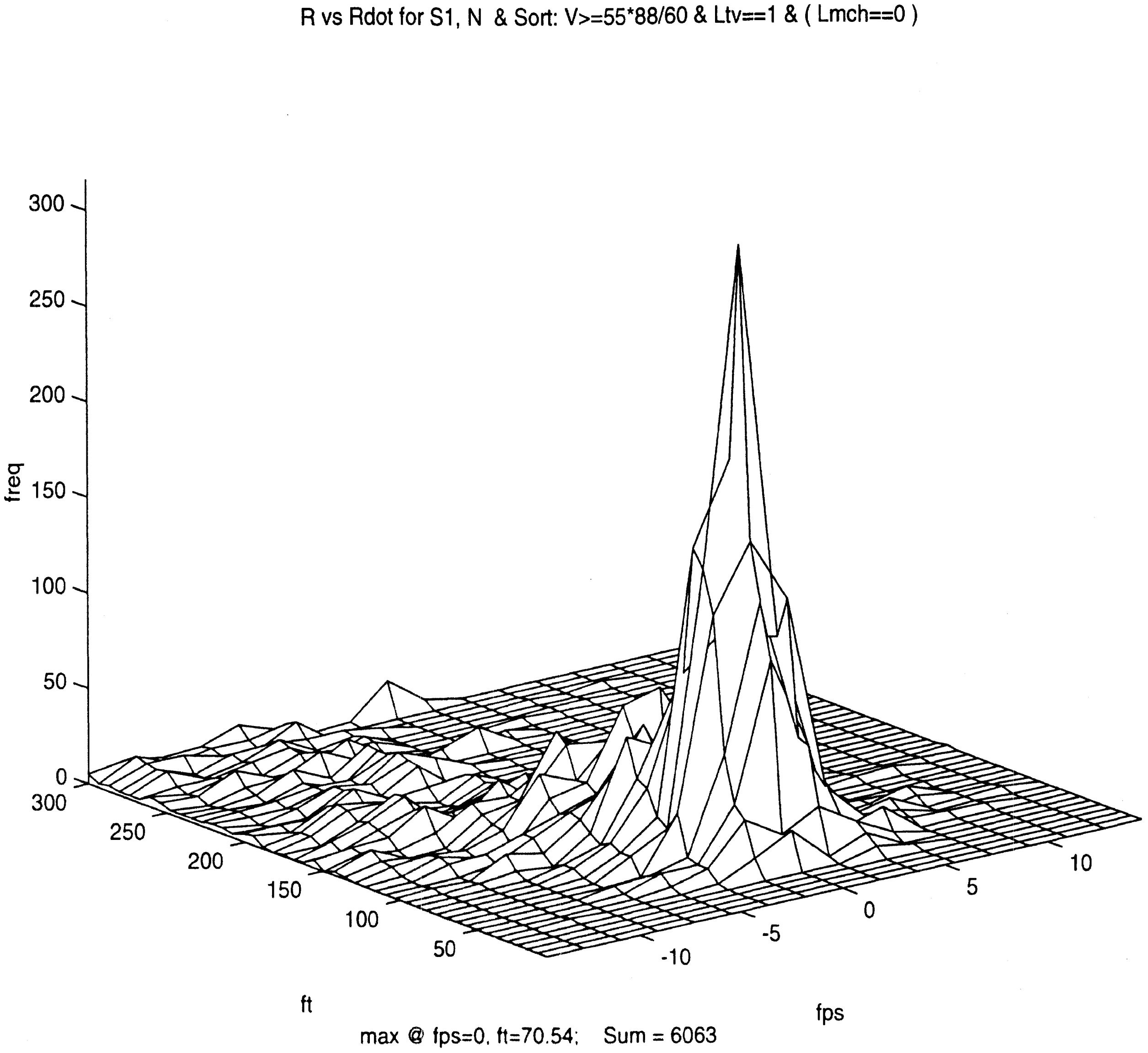
2. "Test Definition and Project Plan," delivered to NHTSA as part of the project entitled "Intelligent Cruise Control Field Operational Test," DTNH22-95-H-07428, The University of Michigan Transportation Research Institute, Ann Arbor, Michigan, Feb. 29, 1996.
3. Hoffman, E.R., "Perception of Relative Velocity," Studies of Automobile and Truck Rear Lighting and Signaling Systems, Rept. No. UM-HSRI-HF-74-25, University of Michigan, HSRI, Ann Arbor, MI, November 1974.
4. Nilsson, L., "Safety Effects of Adaptive Cruise Controls in Critical Traffic Situations," *Proceedings of the Second World Congress on Intelligent Transport Systems - '95 Yokohama*, Yokohama, Japan, November 9-11, 1995.

Appendix A.

Range vs. Range-Rate Histograms for All 36 Drivers During Manual Operation.

Figure A-1. Range vs. Range-Rate Histogram for Subject #1, Manual Driving.



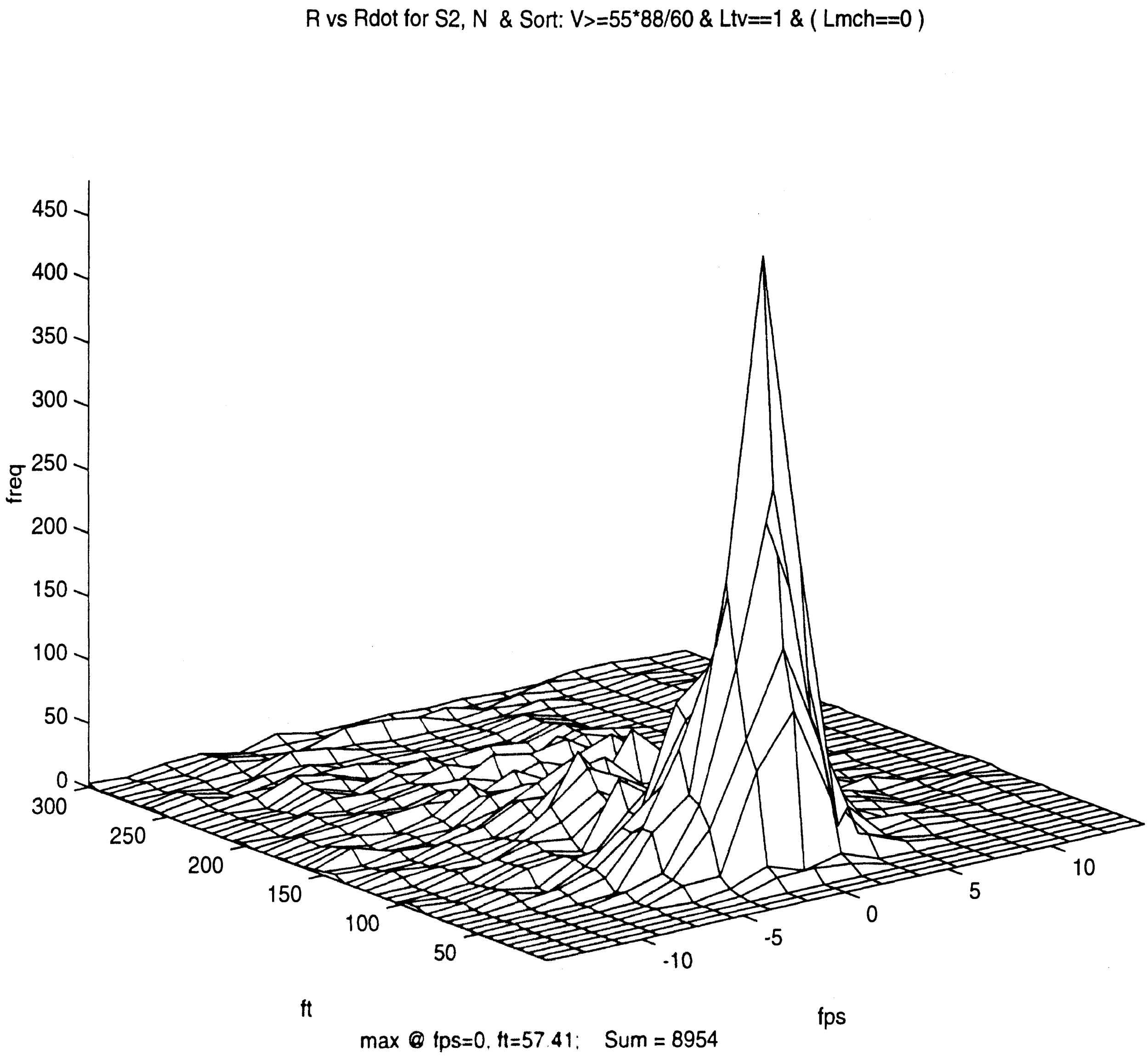


Figure A-2. Range vs. Range-Rate Histogram for Subject #2, Manual Driving.

Figure A-3. Range vs. Range-Rate Histogram for Subject #3, Manual Driving.

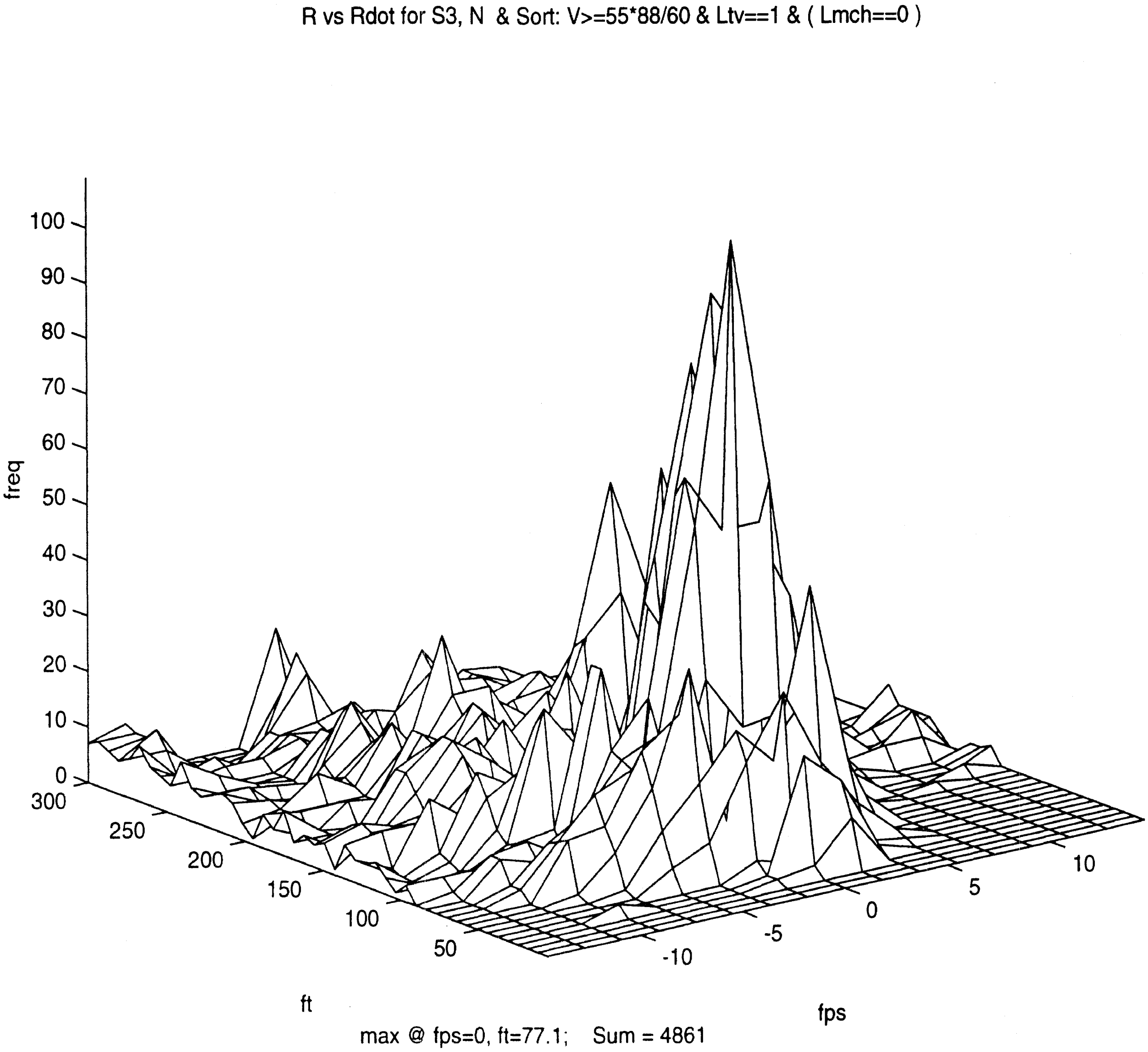


Figure A-4. Range vs. Range-Rate Histogram for Subject #4, Manual Driving.

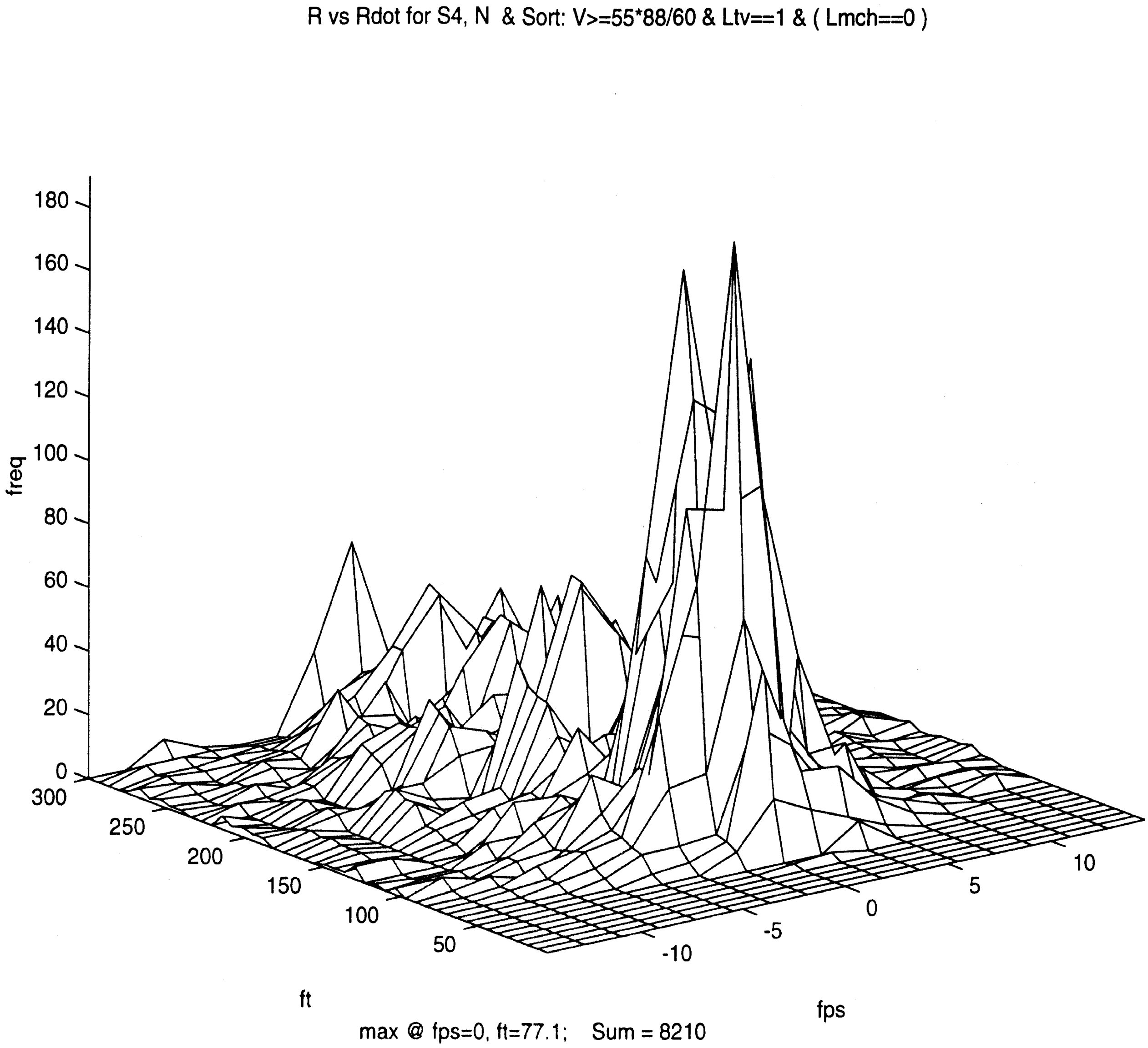


Figure A-5. Range vs. Range-Rate Histogram for Subject #5, Manual Driving.

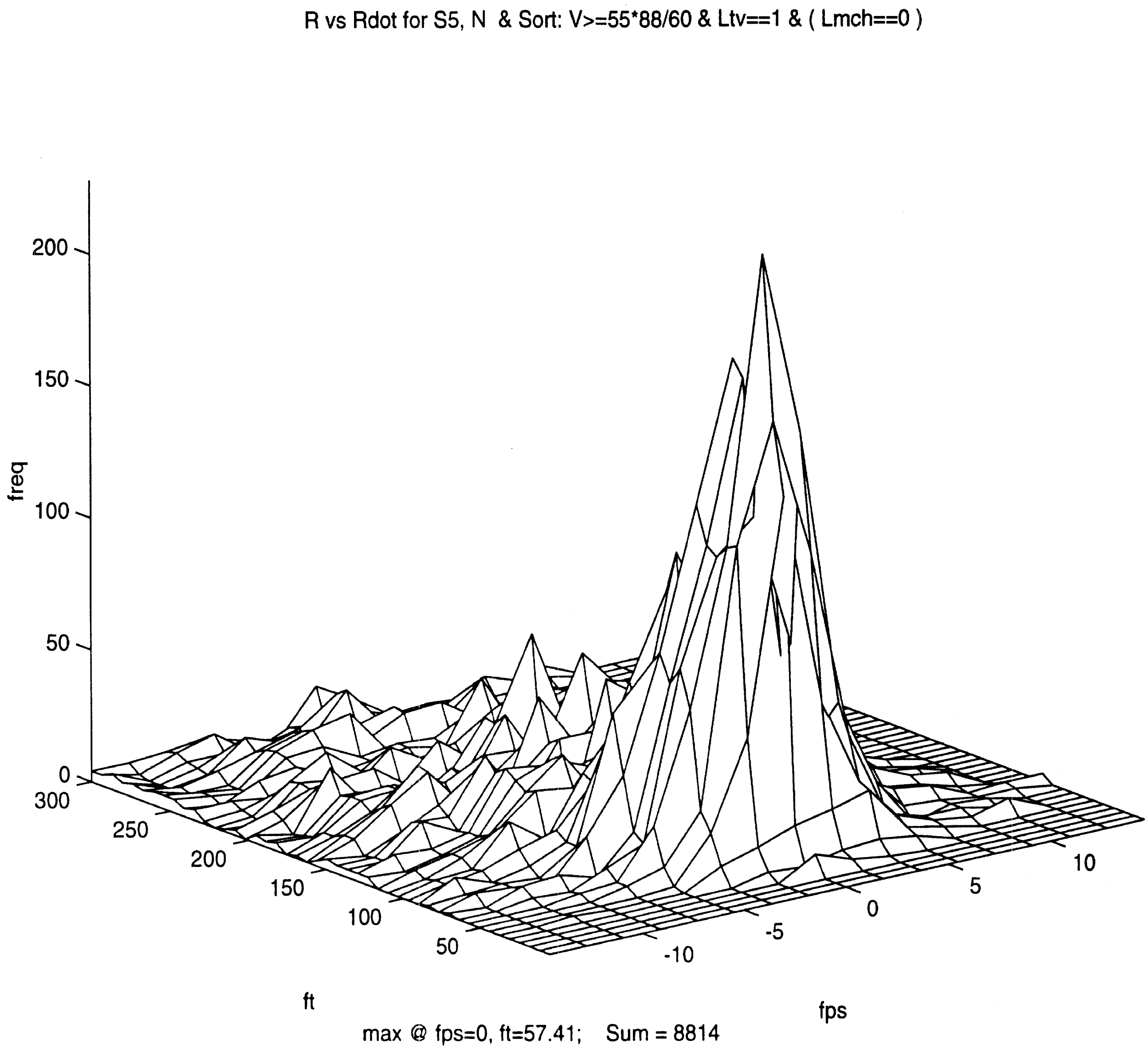


Figure A-6. Range vs. Range-Rate Histogram for Subject #6, Manual Driving.

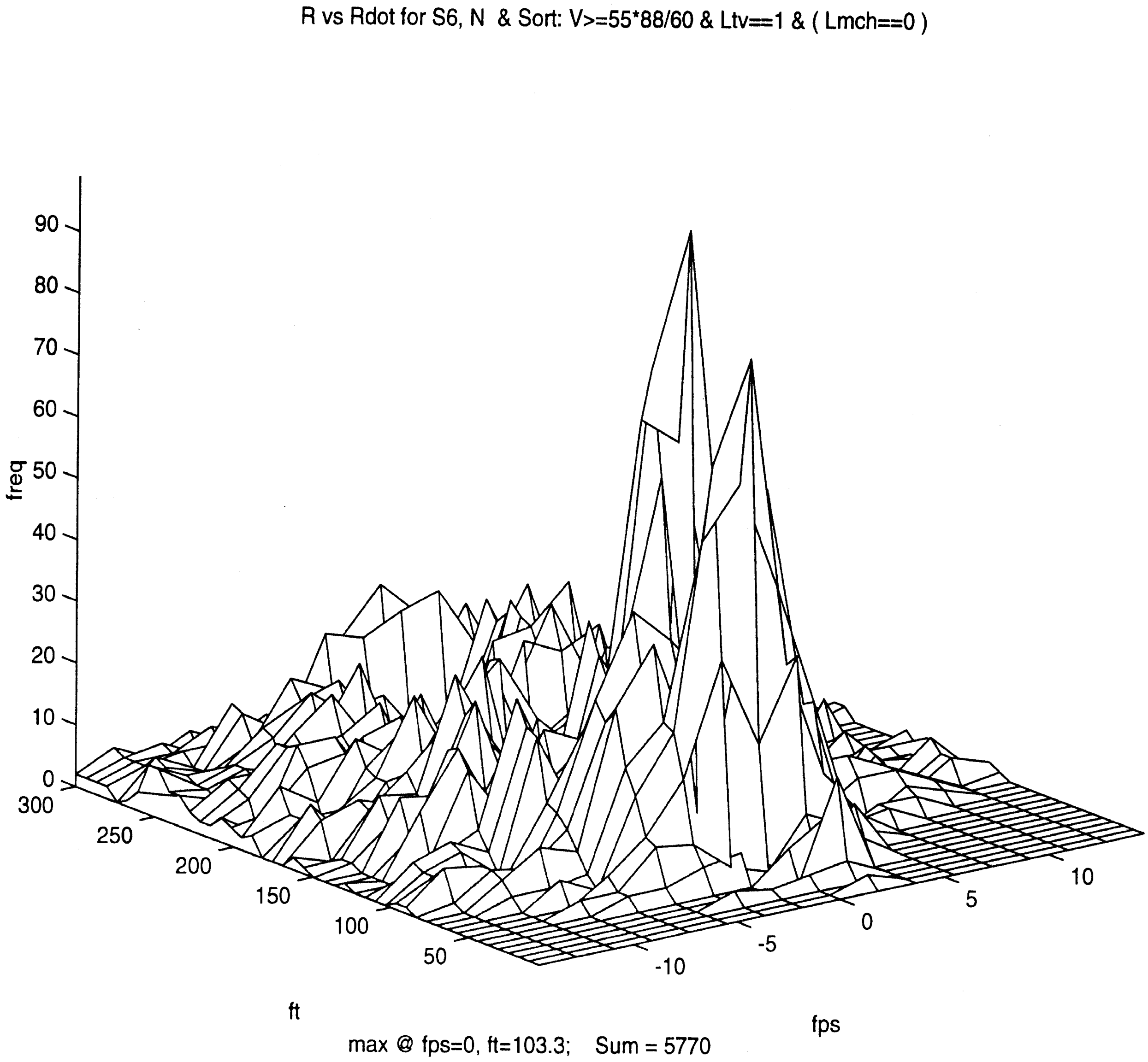


Figure A-7. Range vs. Range-Rate Histogram for Subject #7, Manual Driving.

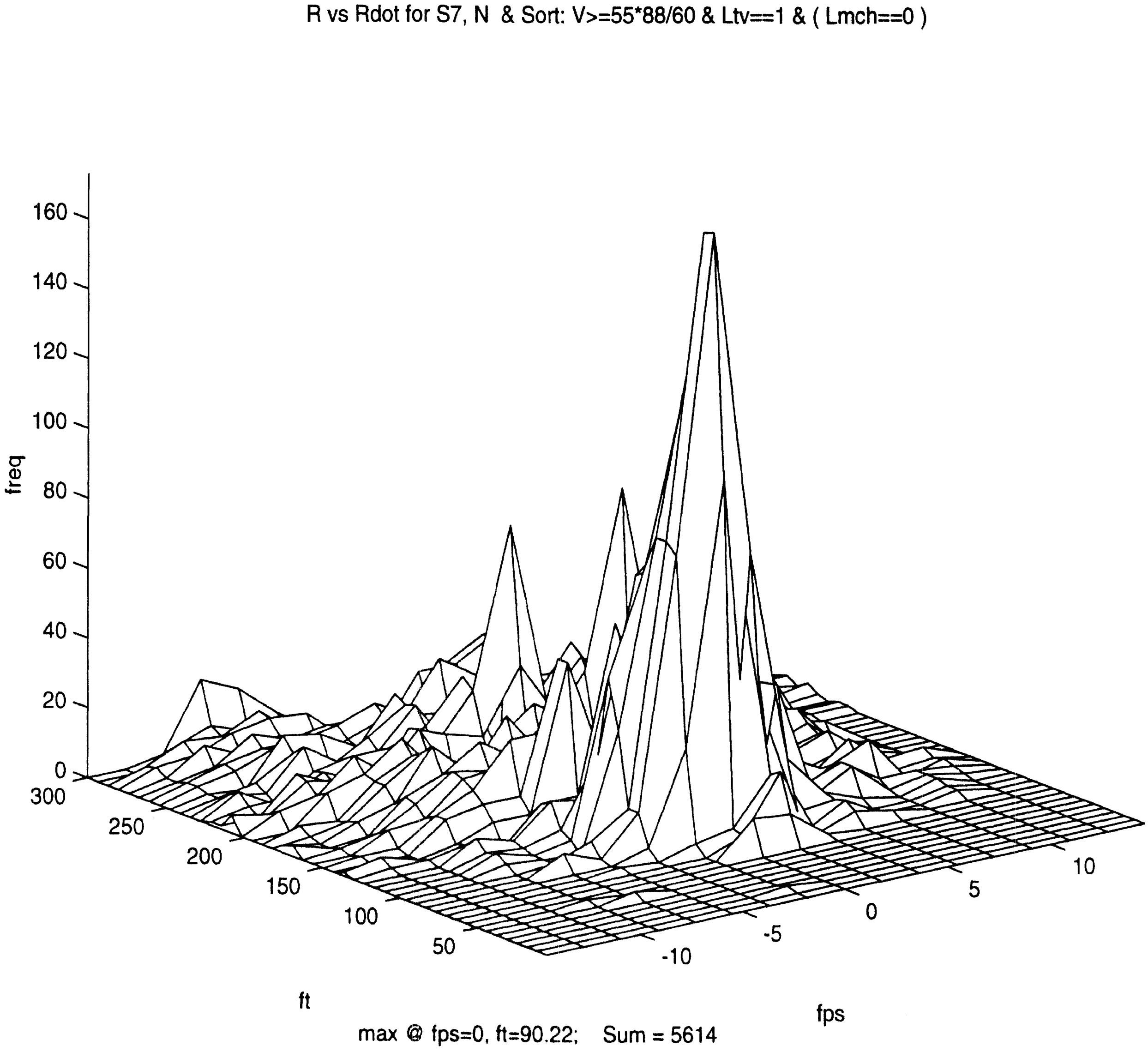


Figure A-8. Range vs. Range-Rate Histogram for Subject #8, Manual Driving.

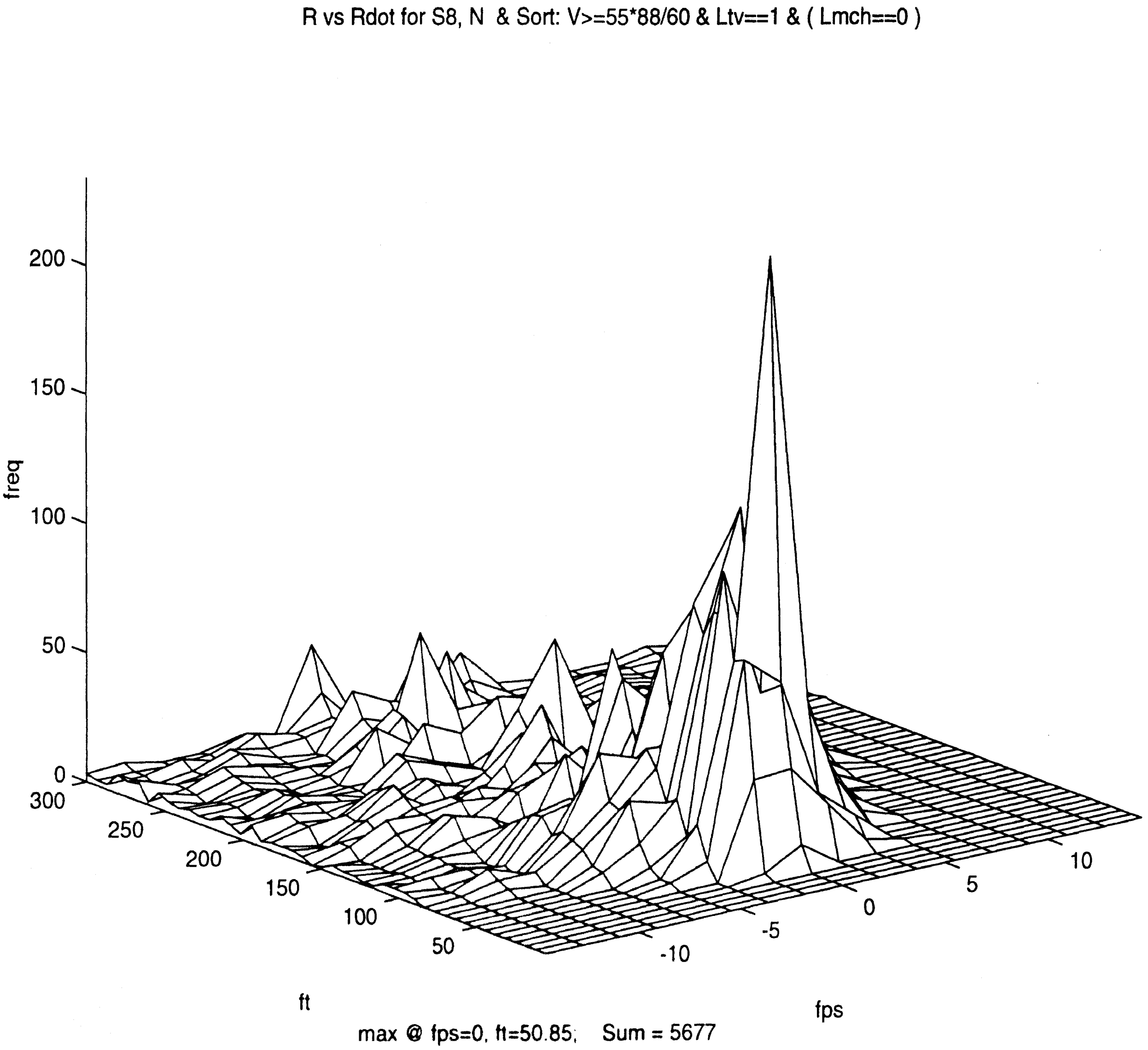


Figure A-9. Range vs. Range-Rate Histogram for Subject #9, Manual Driving.

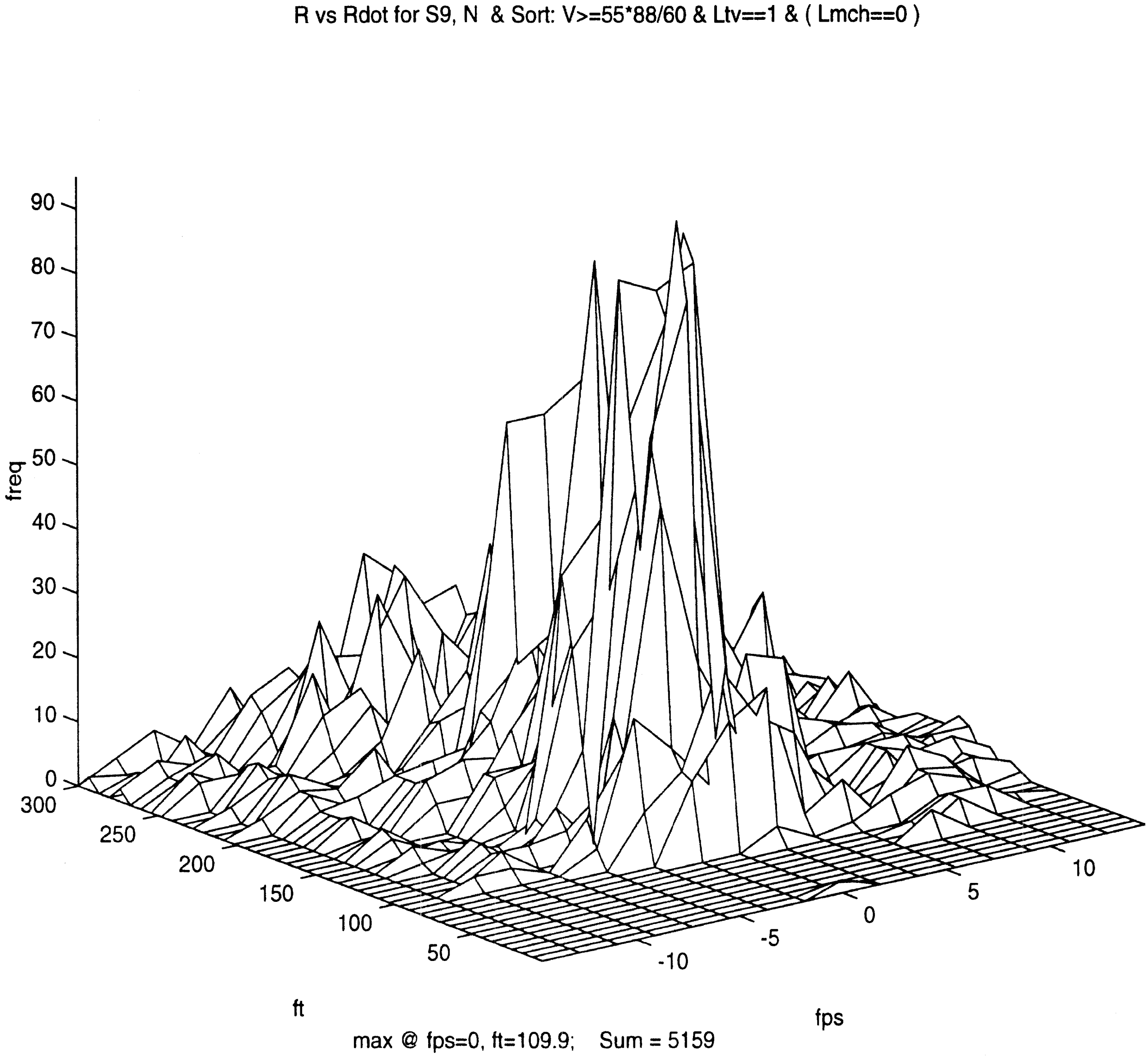


Figure A-10. Range vs. Range-Rate Histogram for Subject #10, Manual Driving.

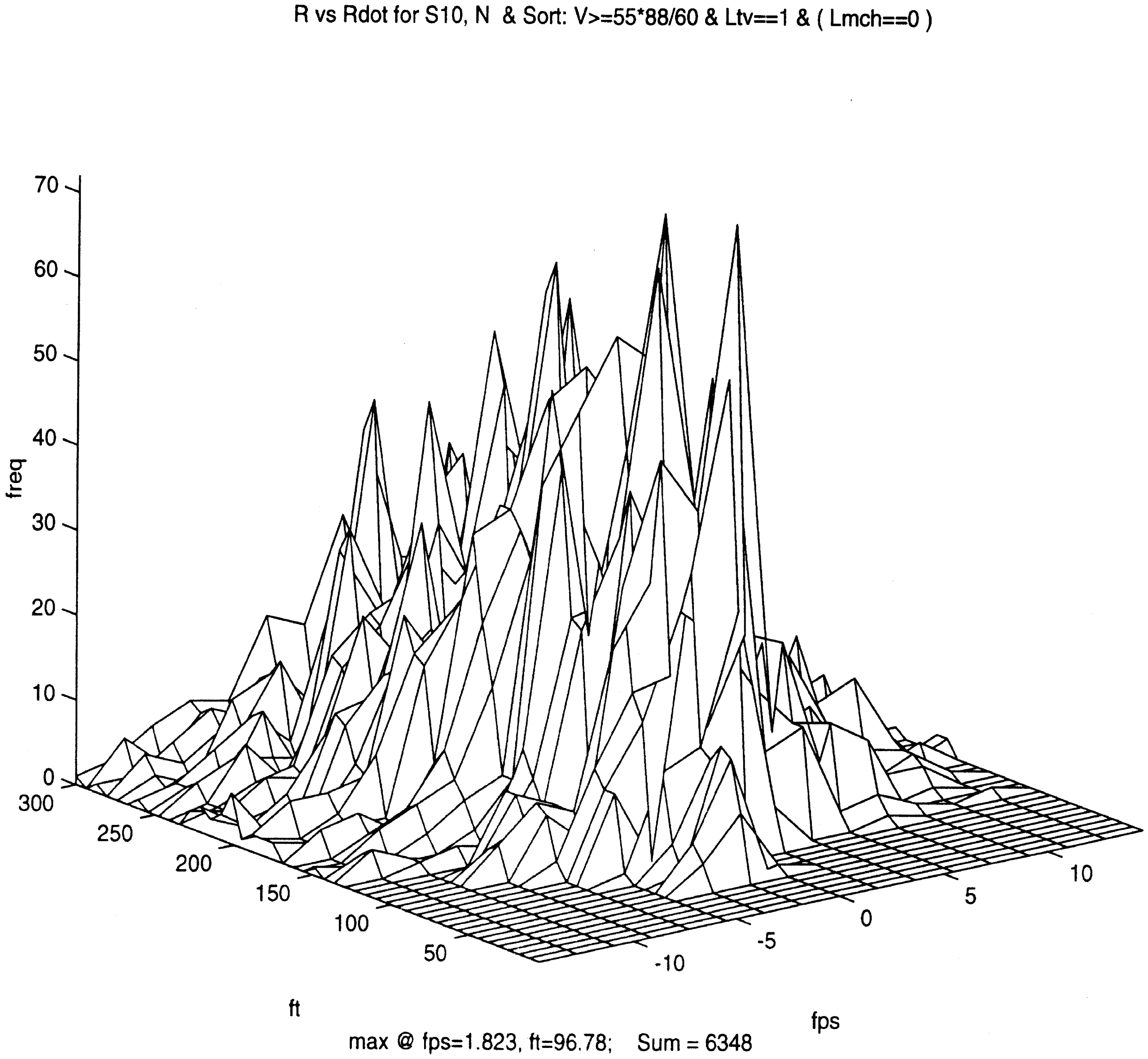


Figure A-11. Range vs. Range-Rate Histogram for Subject #11, Manual Driving.

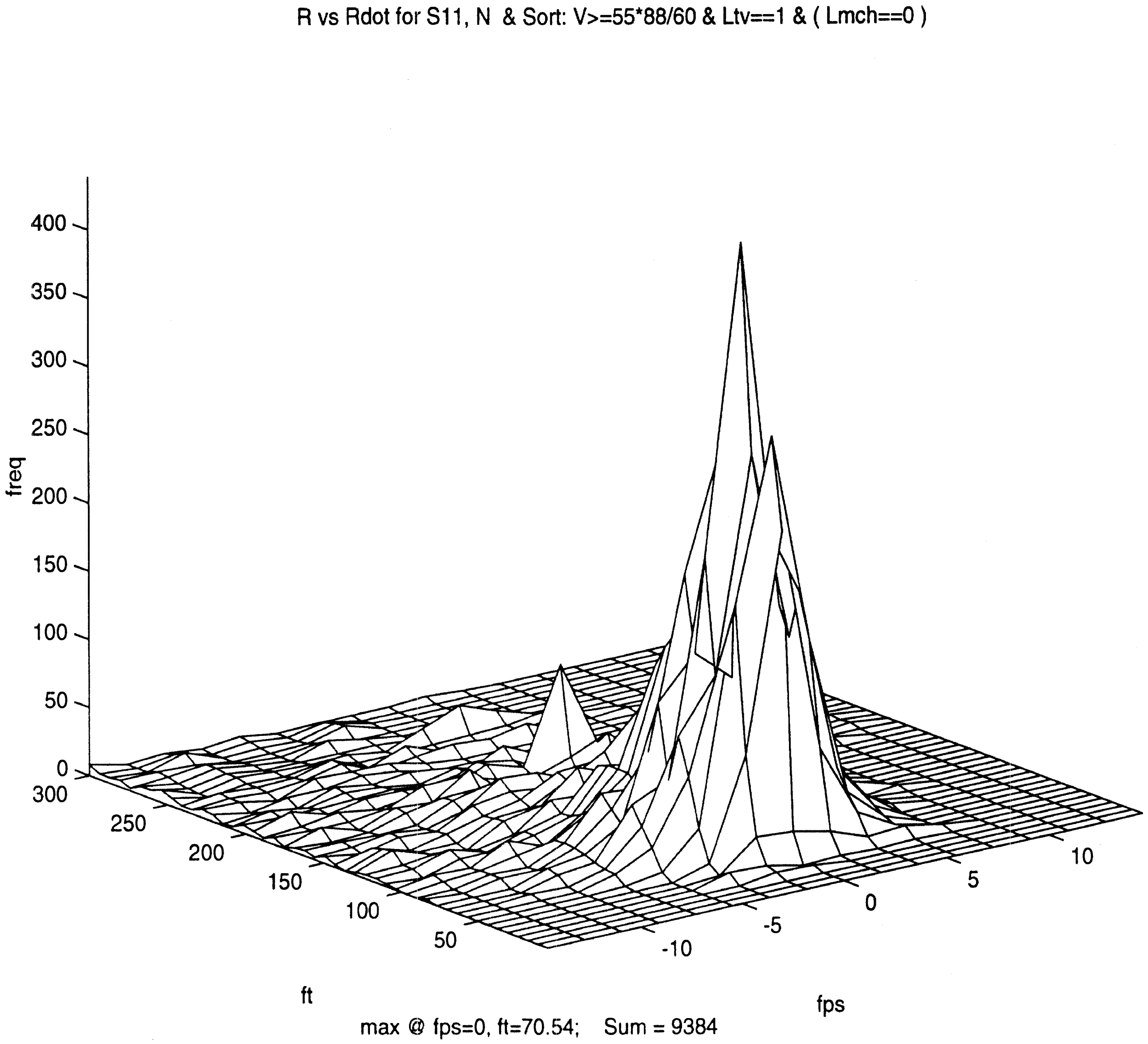


Figure A-12. Range vs. Range-Rate Histogram for Subject #12, Manual Driving.

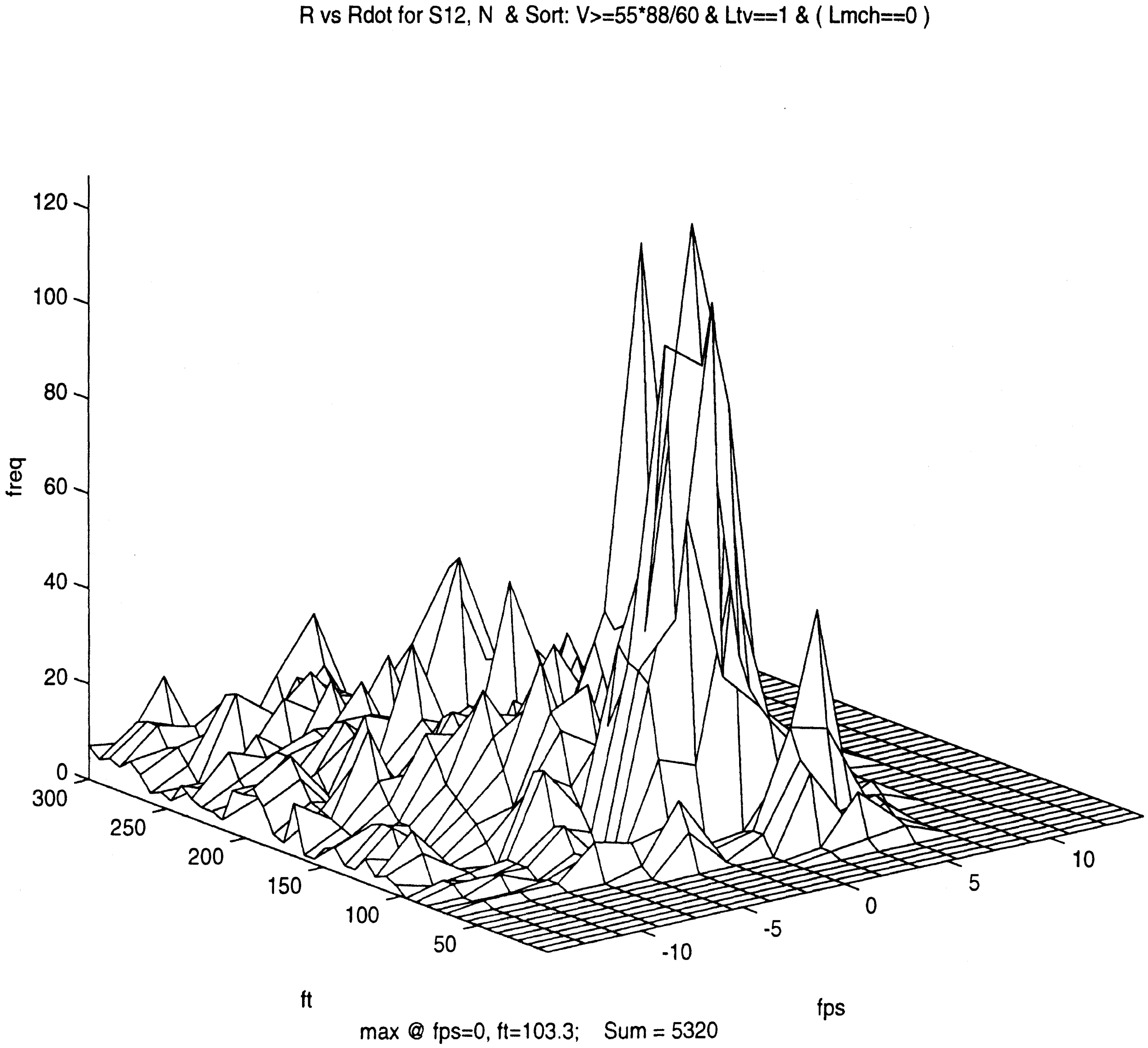


Figure A-13. Range vs. Range-Rate Histogram for Subject #13, Manual Driving.

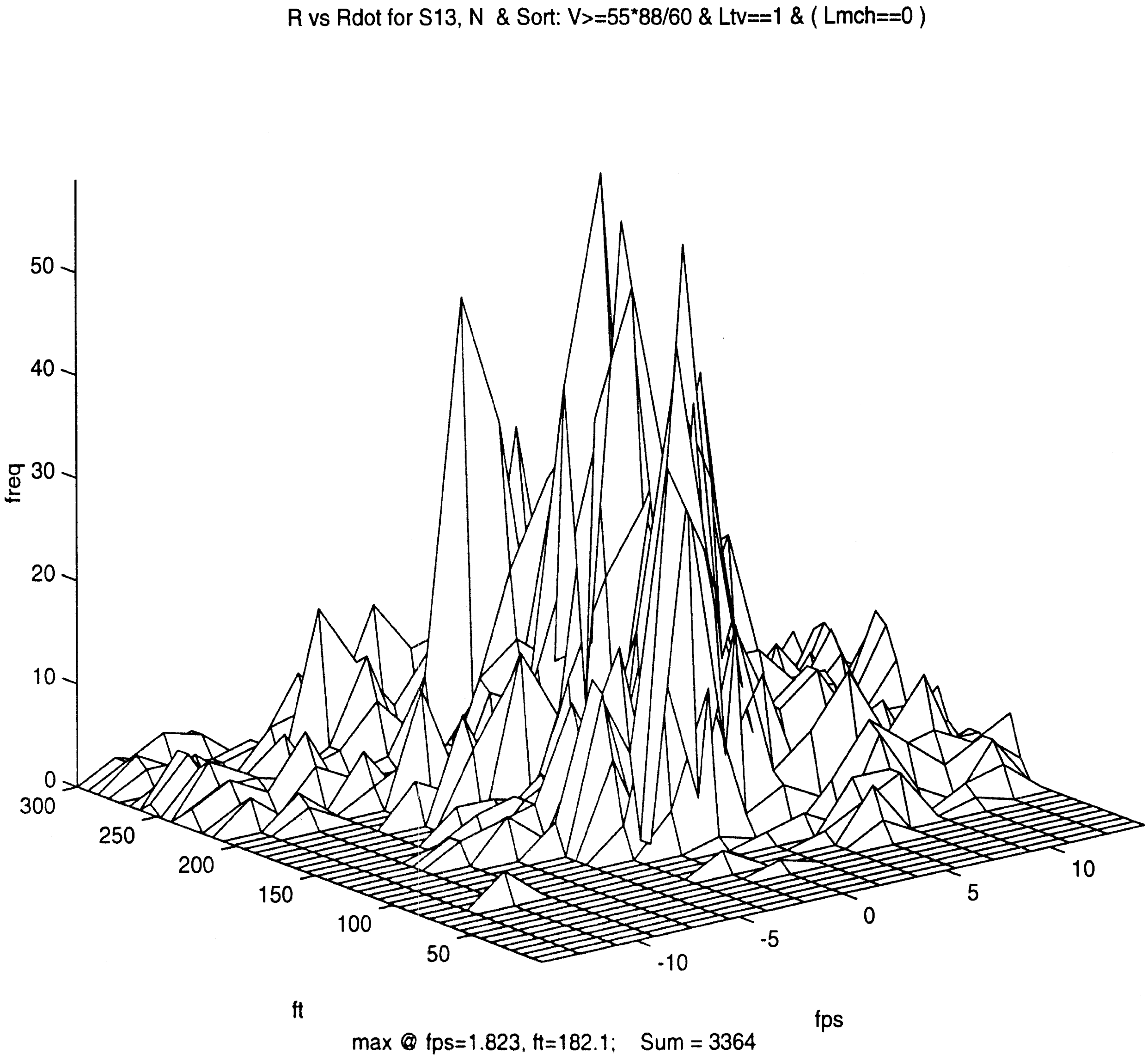


Figure A-14. Range vs. Range-Rate Histogram for Subject #14, Manual Driving.

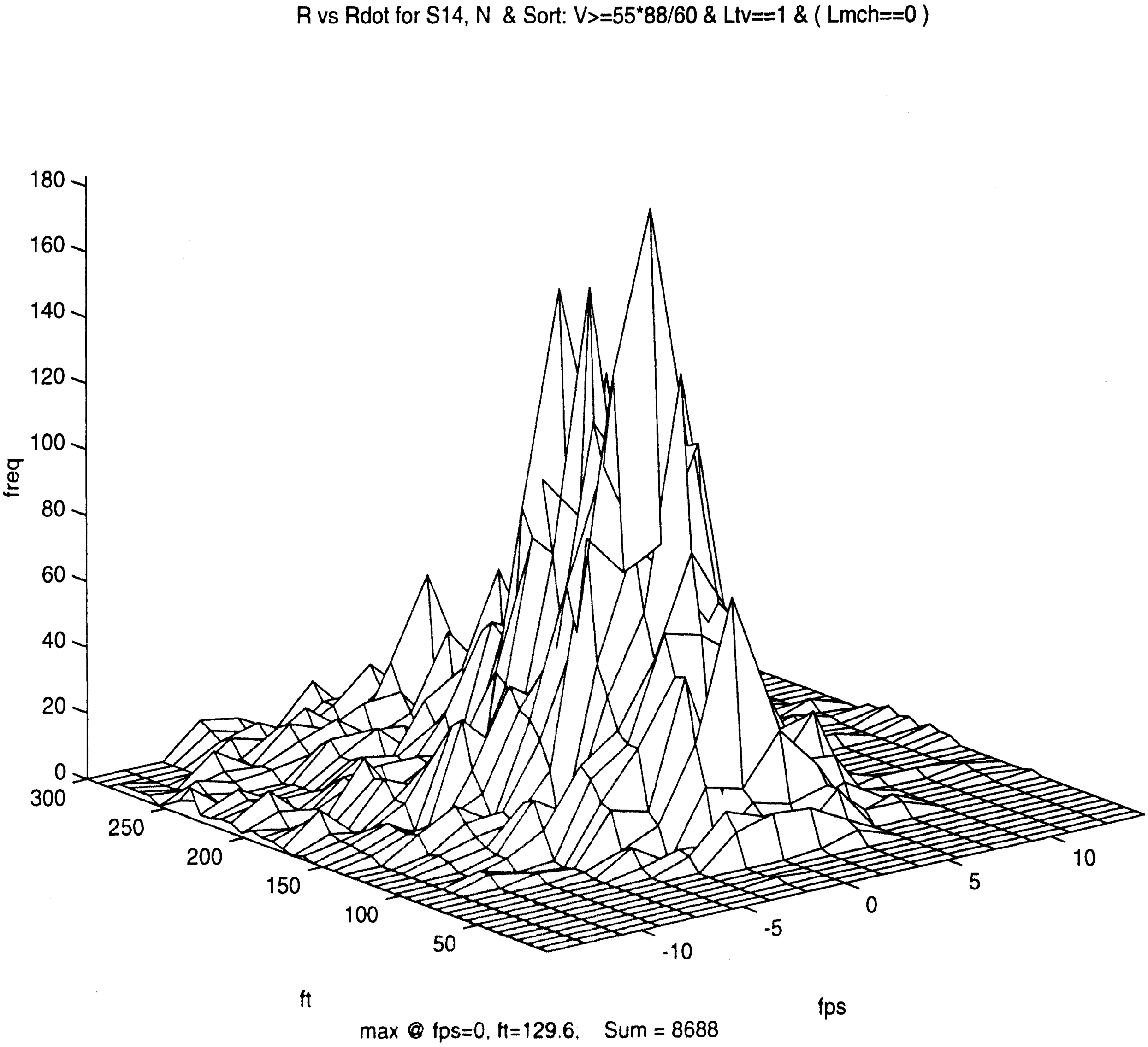
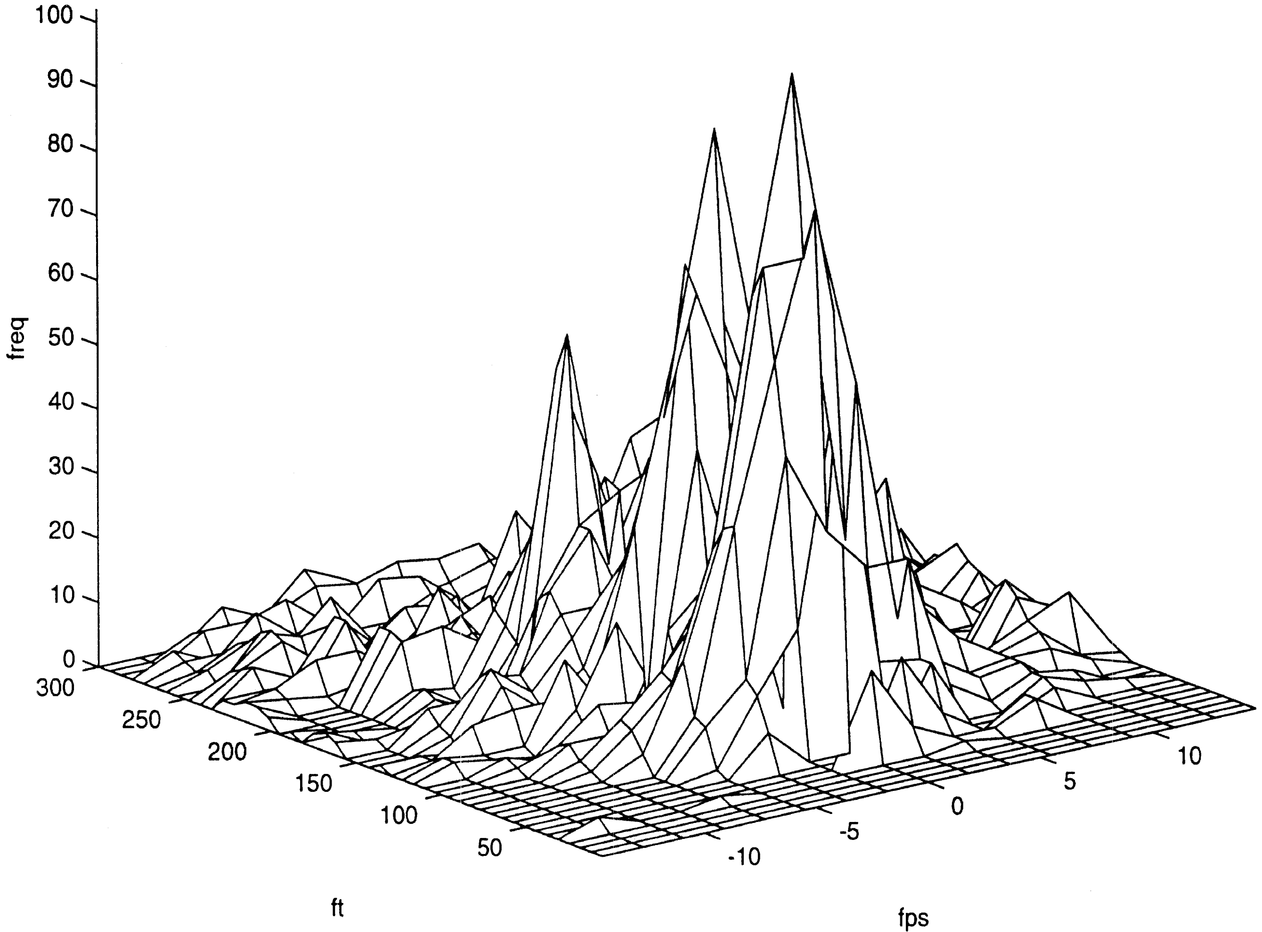


Figure A-15. Range vs. Range-Rate Histogram for Subject #15, Manual Driving.

R vs Rdot for S15, N & Sort: V>=55*88/60 & Ltv==1 & (Lmch==0)



max @ fps=0, ft=83.66; Sum = 5308

Figure A-16. Range vs. Range-Rate Histogram for Subject #16, Manual Driving.

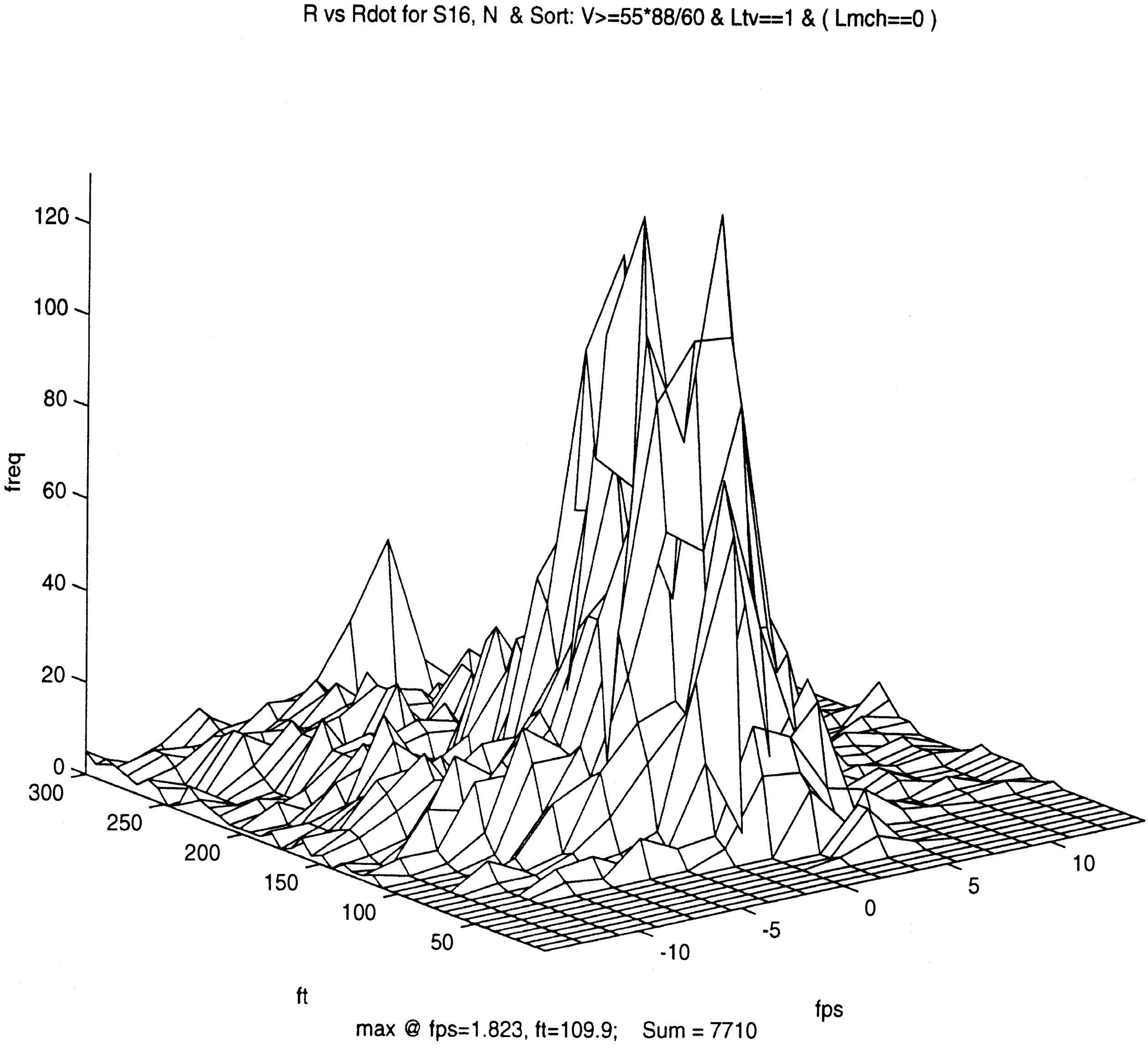


Figure A-17. Range vs. Range-Rate Histogram for Subject #17, Manual Driving.

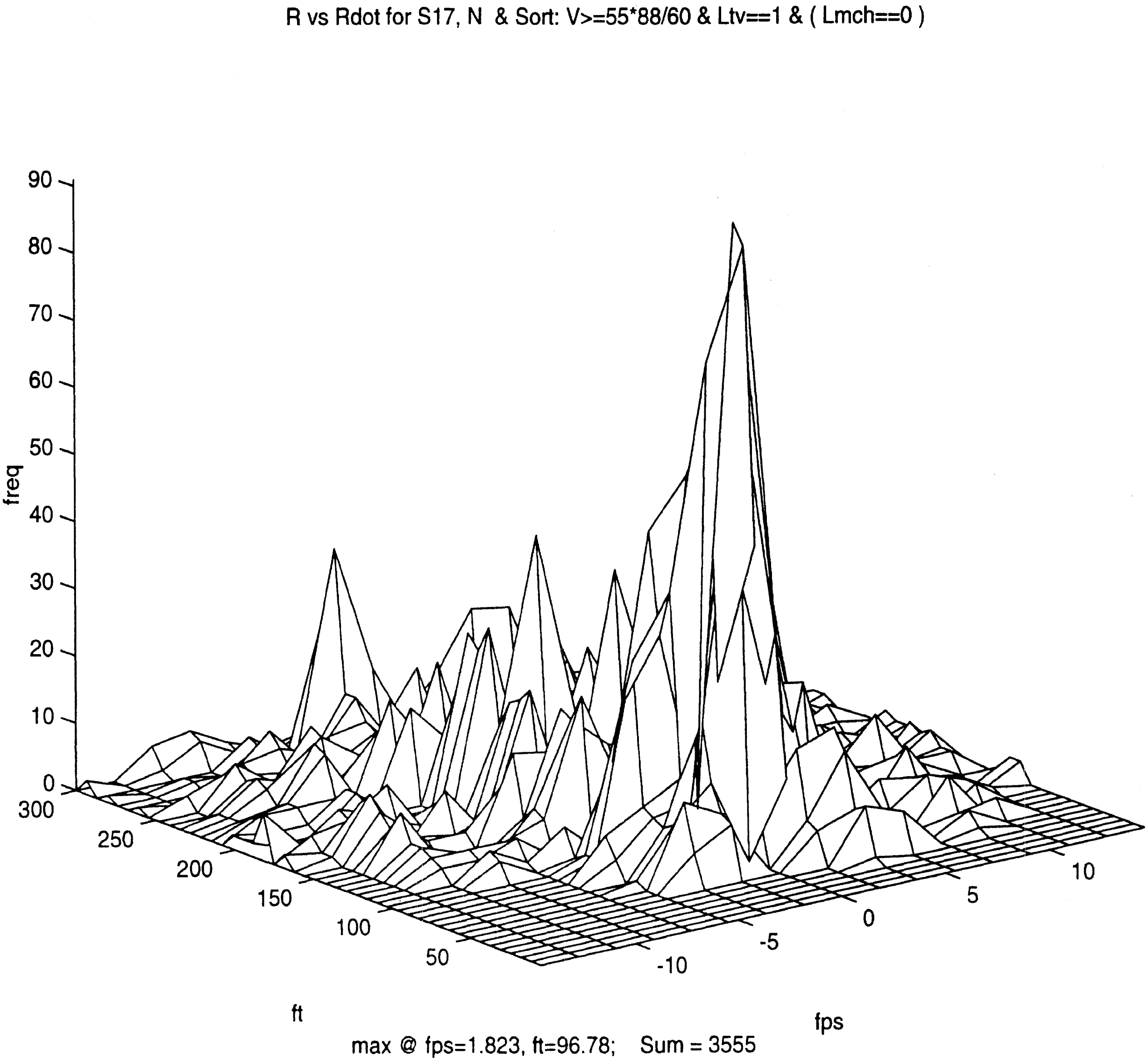


Figure A-18. Range vs. Range-Rate Histogram for Subject #18, Manual Driving.

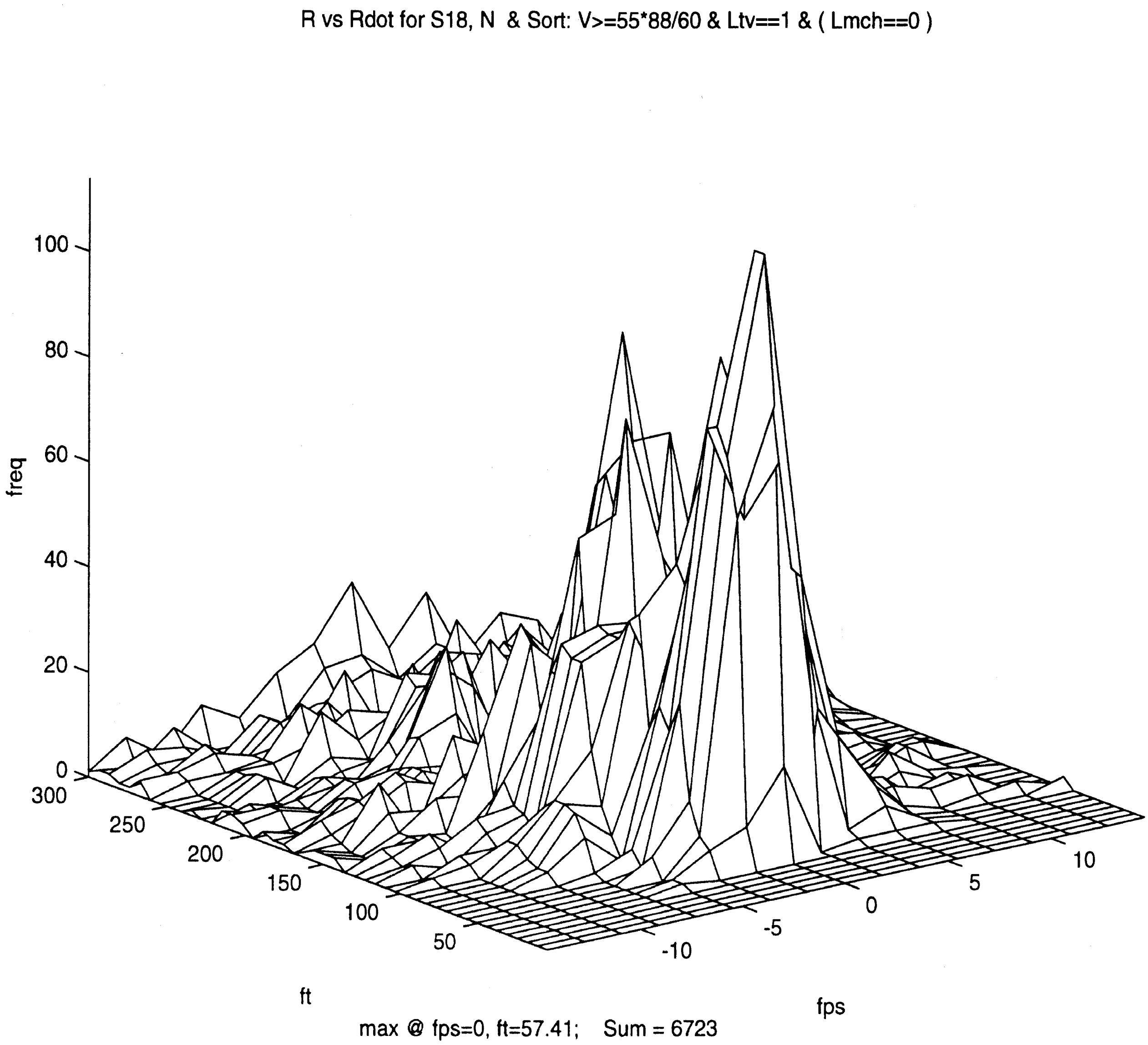


Figure A-19. Range vs. Range-Rate Histogram for Subject #19, Manual Driving.

R vs Rdot for S19, N & Sort: V>=55*88/60 & Ltv==1 & (Lmch==0)

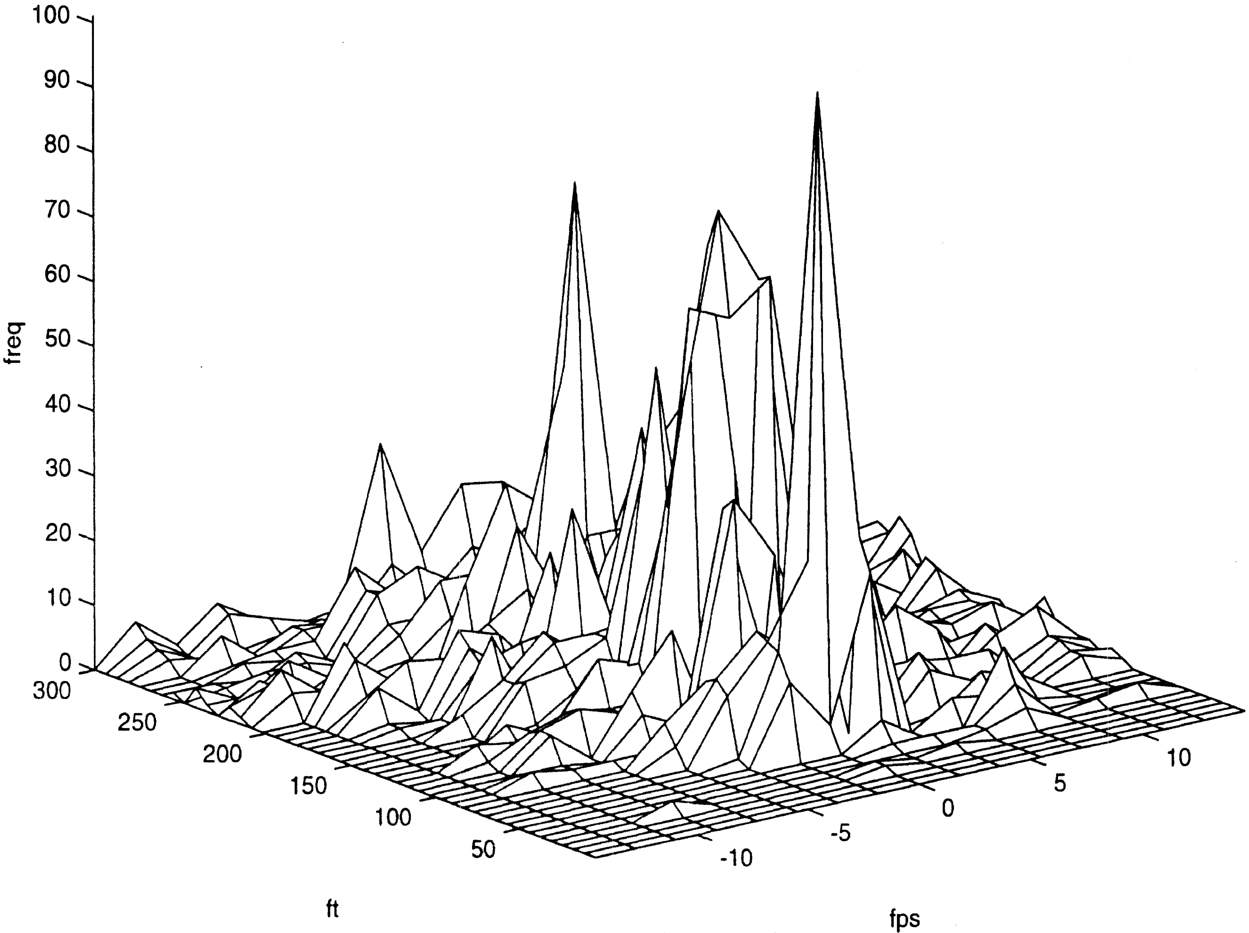


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Figure A-20. Range vs. Range-Rate Histogram for Subject #20, Manual Driving.

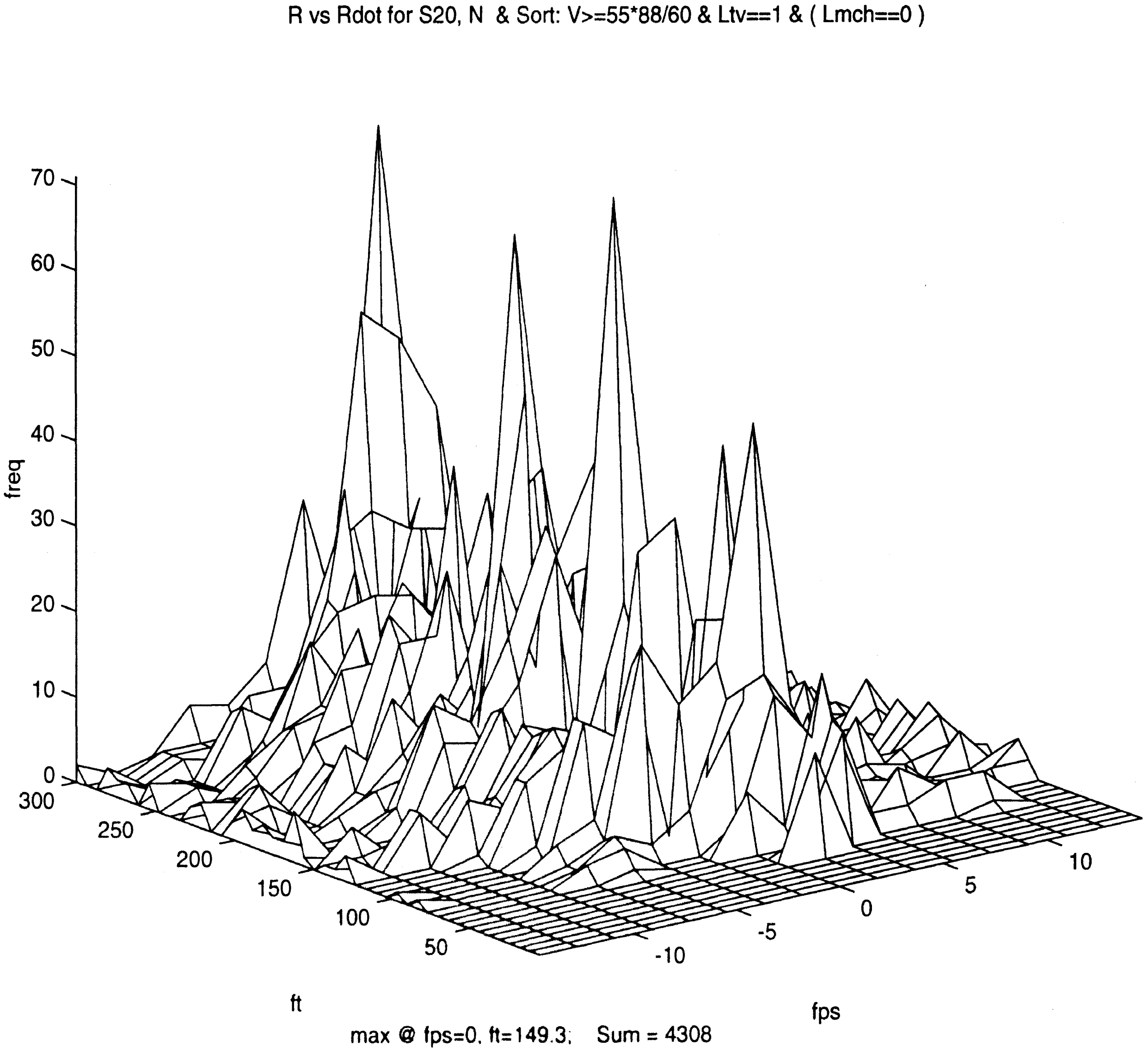


Figure A-21. Range vs. Range-Rate Histogram for Subject #21, Manual Driving.

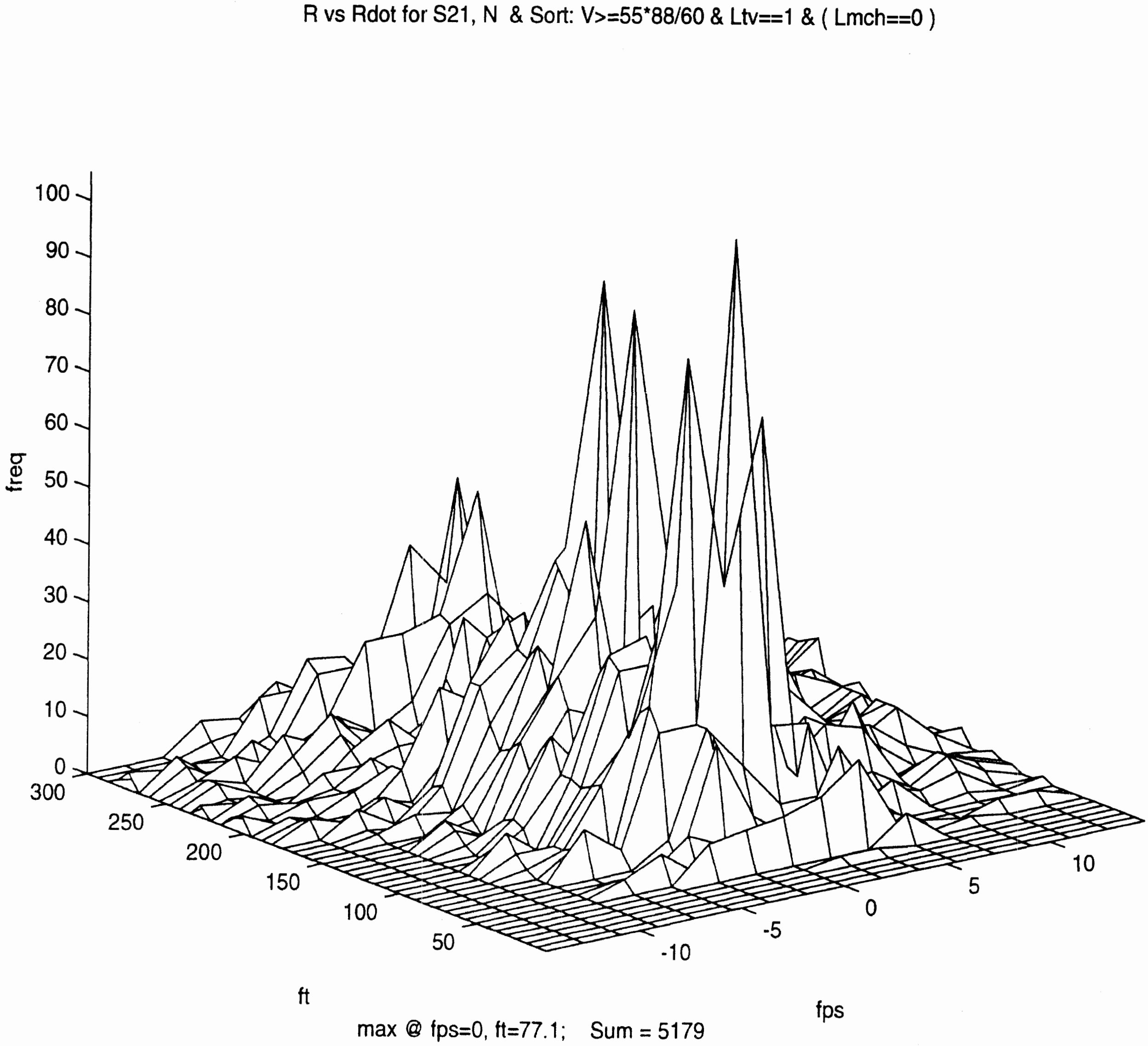


Figure A-22. Range vs. Range-Rate Histogram for Subject #22, Manual Driving.

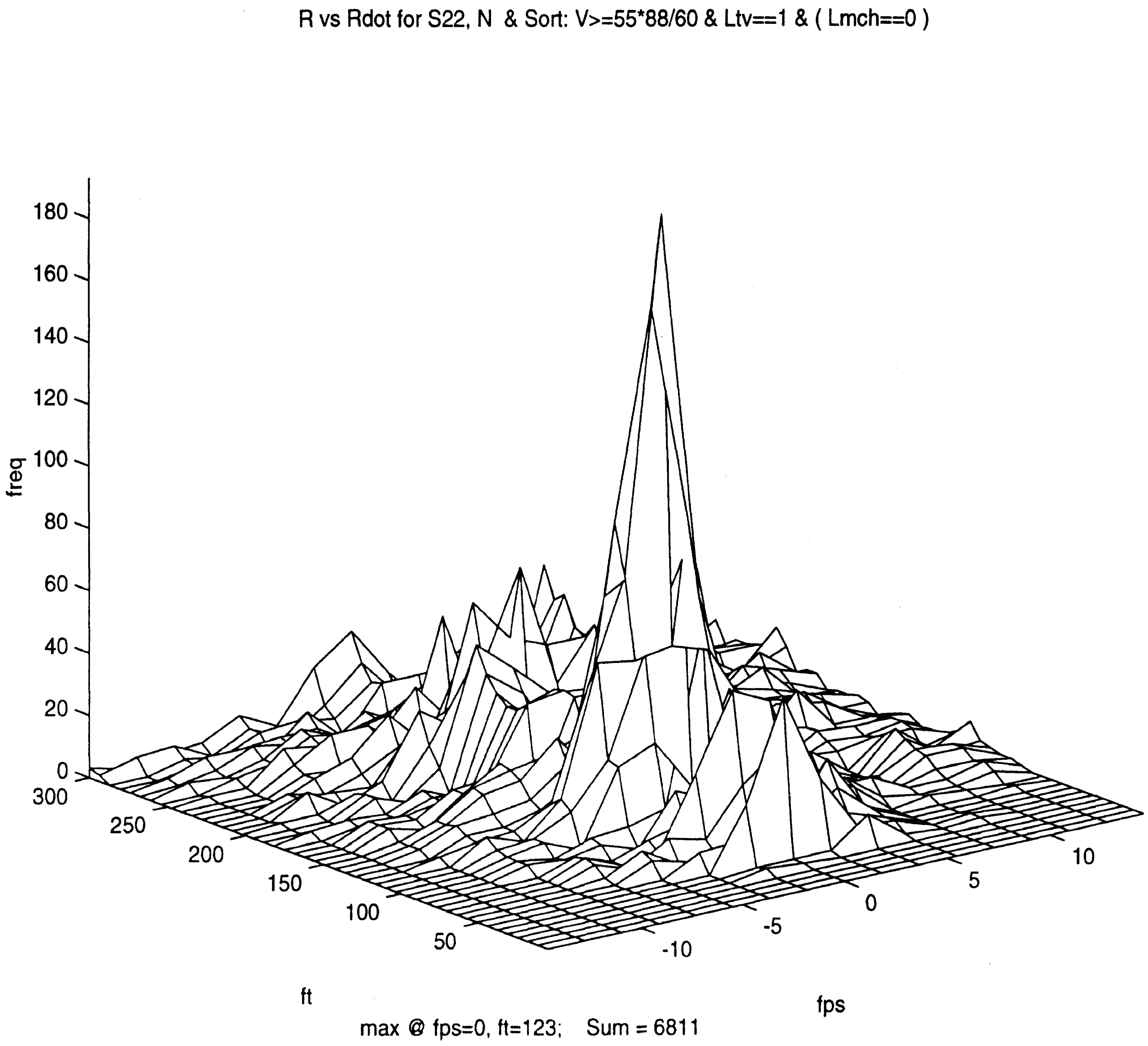


Figure A-23. Range vs. Range-Rate Histogram for Subject #23, Manual Driving.

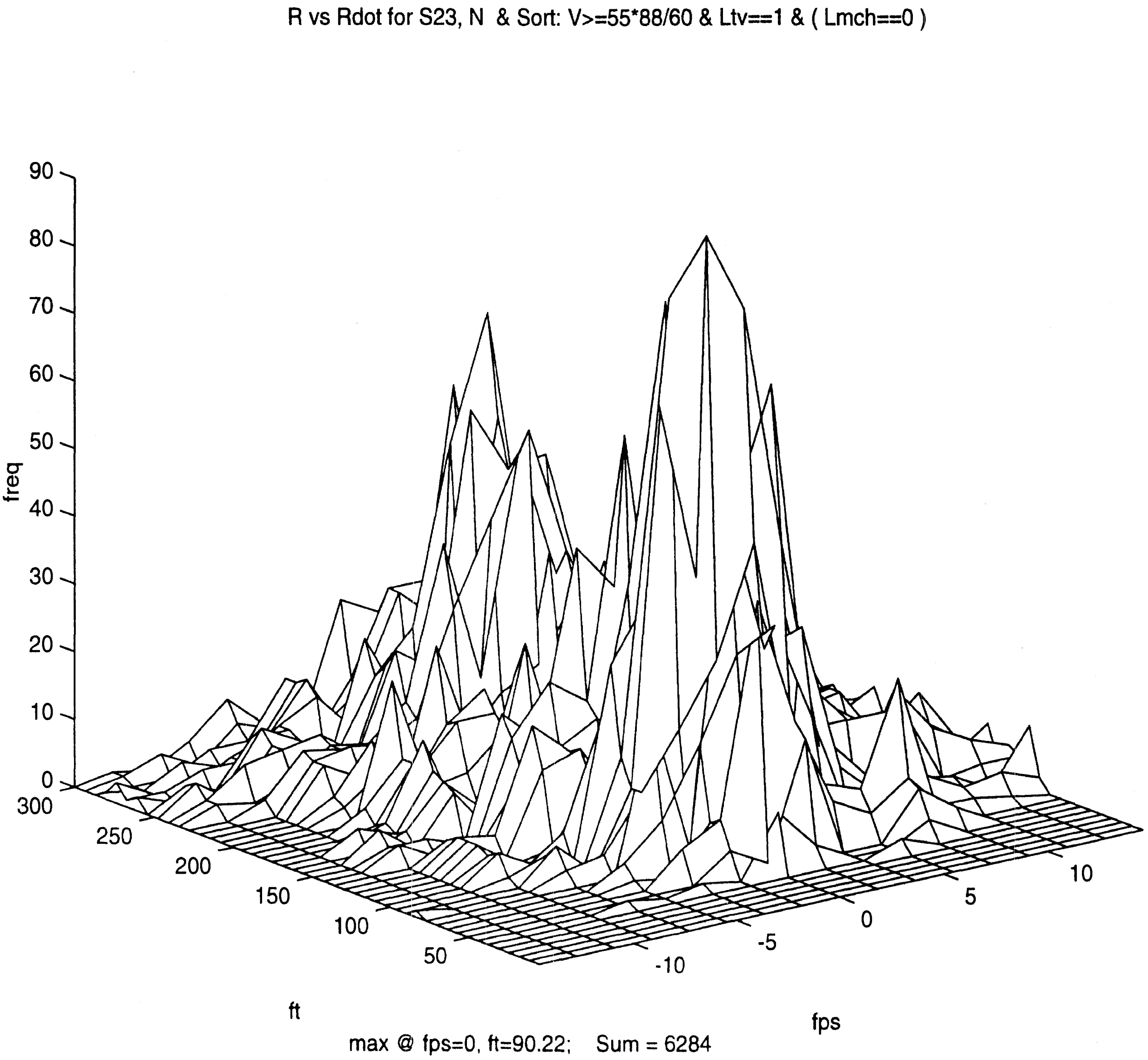


Figure A-24. Range vs. Range-Rate Histogram for Subject #24, Manual Driving.

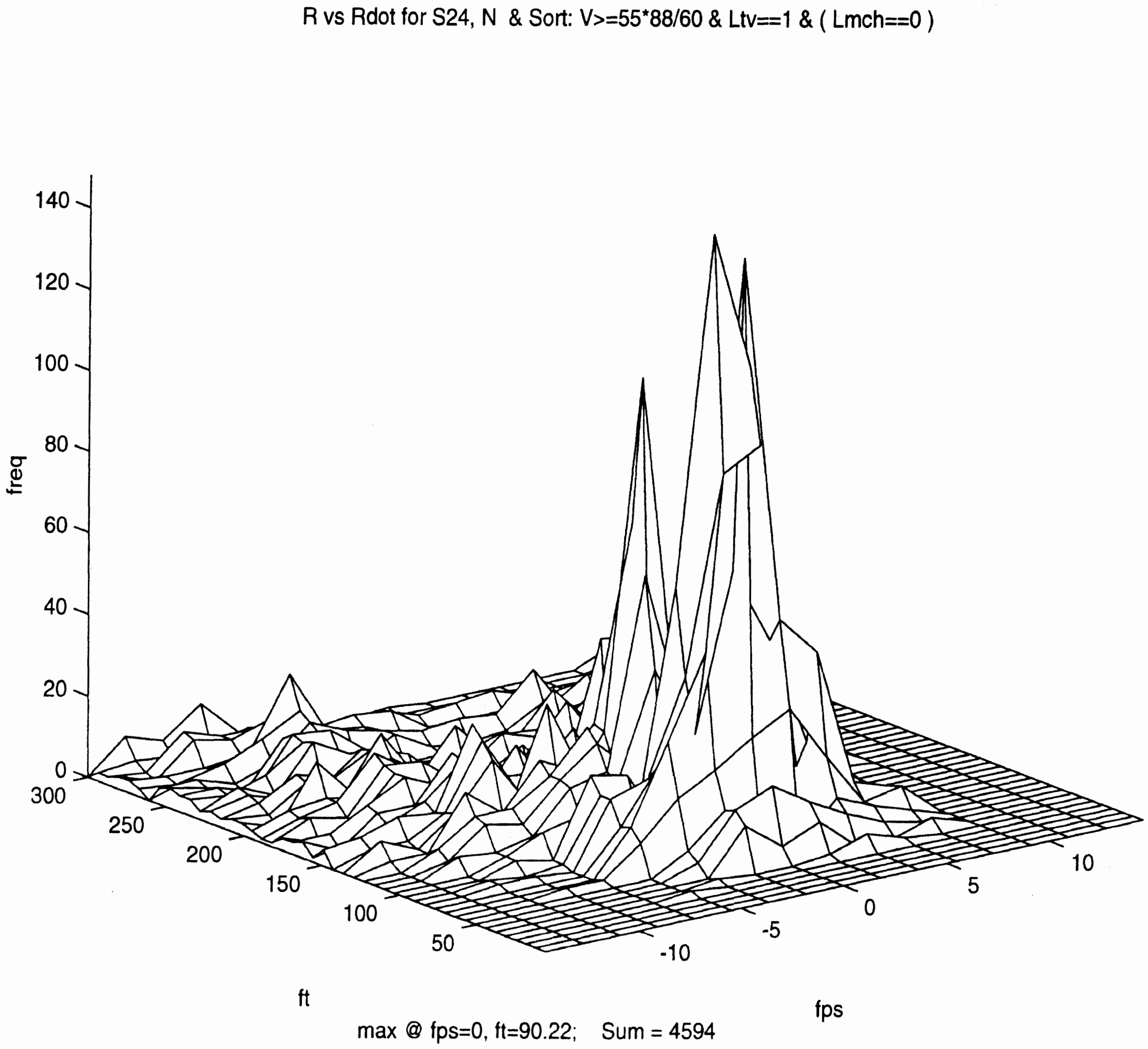


Figure A-25. Range vs. Range-Rate Histogram for Subject #25, Manual Driving.

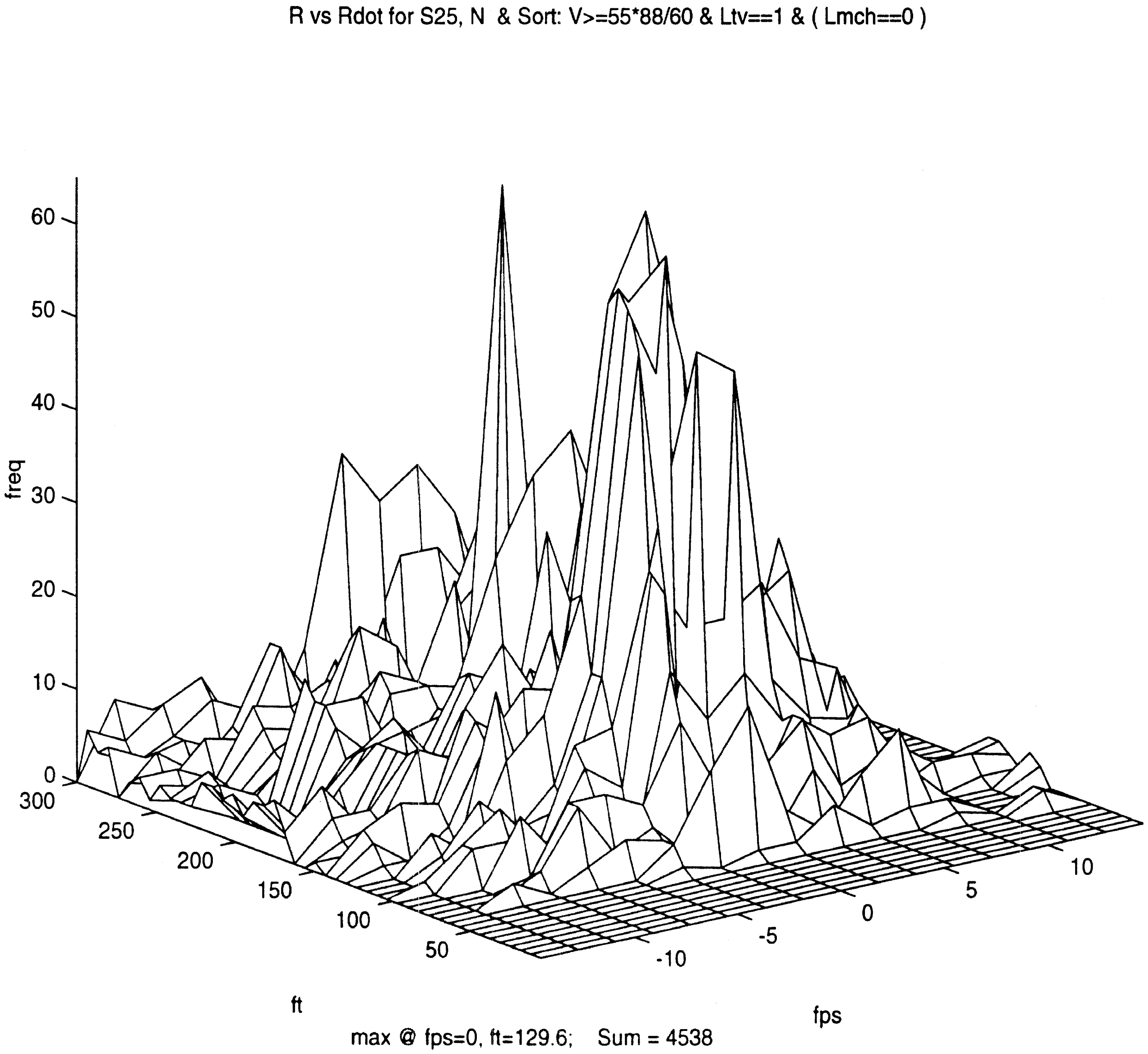


Figure A-26. Range vs. Range-Rate Histogram for Subject #26, Manual Driving.

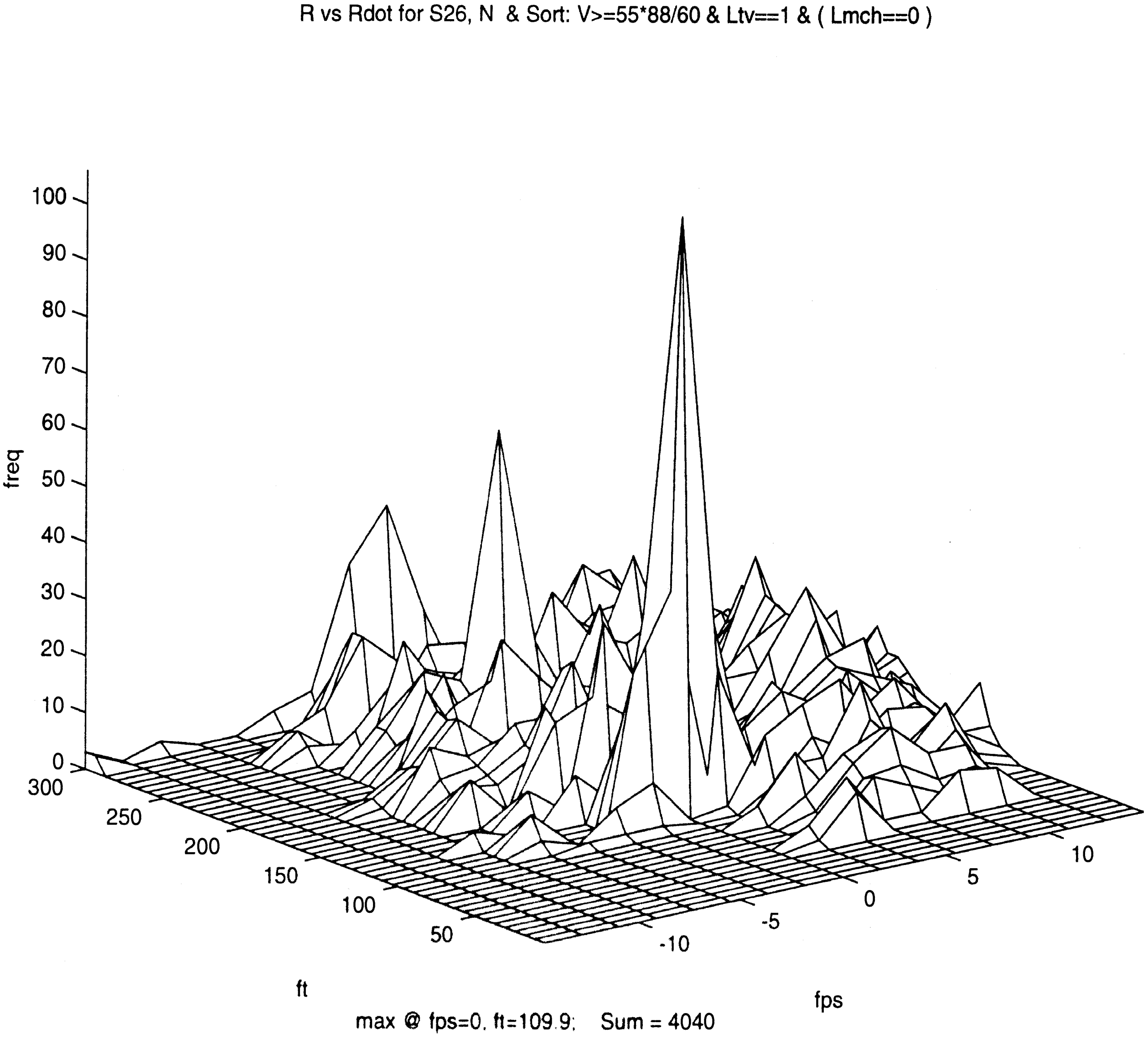


Figure A-27. Range vs. Range-Rate Histogram for Subject #27, Manual Driving.

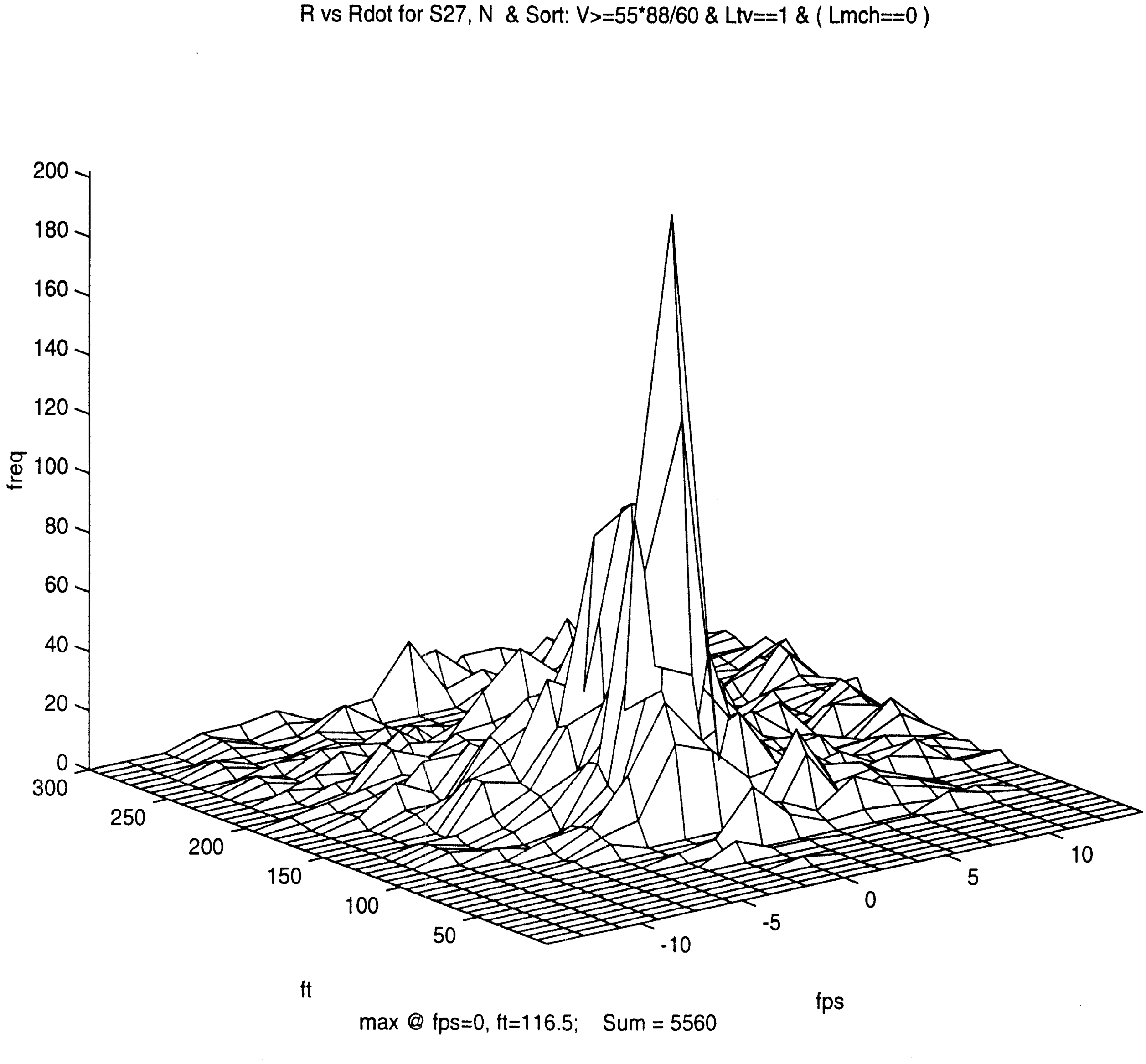


Figure A-28. Range vs. Range-Rate Histogram for Subject #28, Manual Driving.

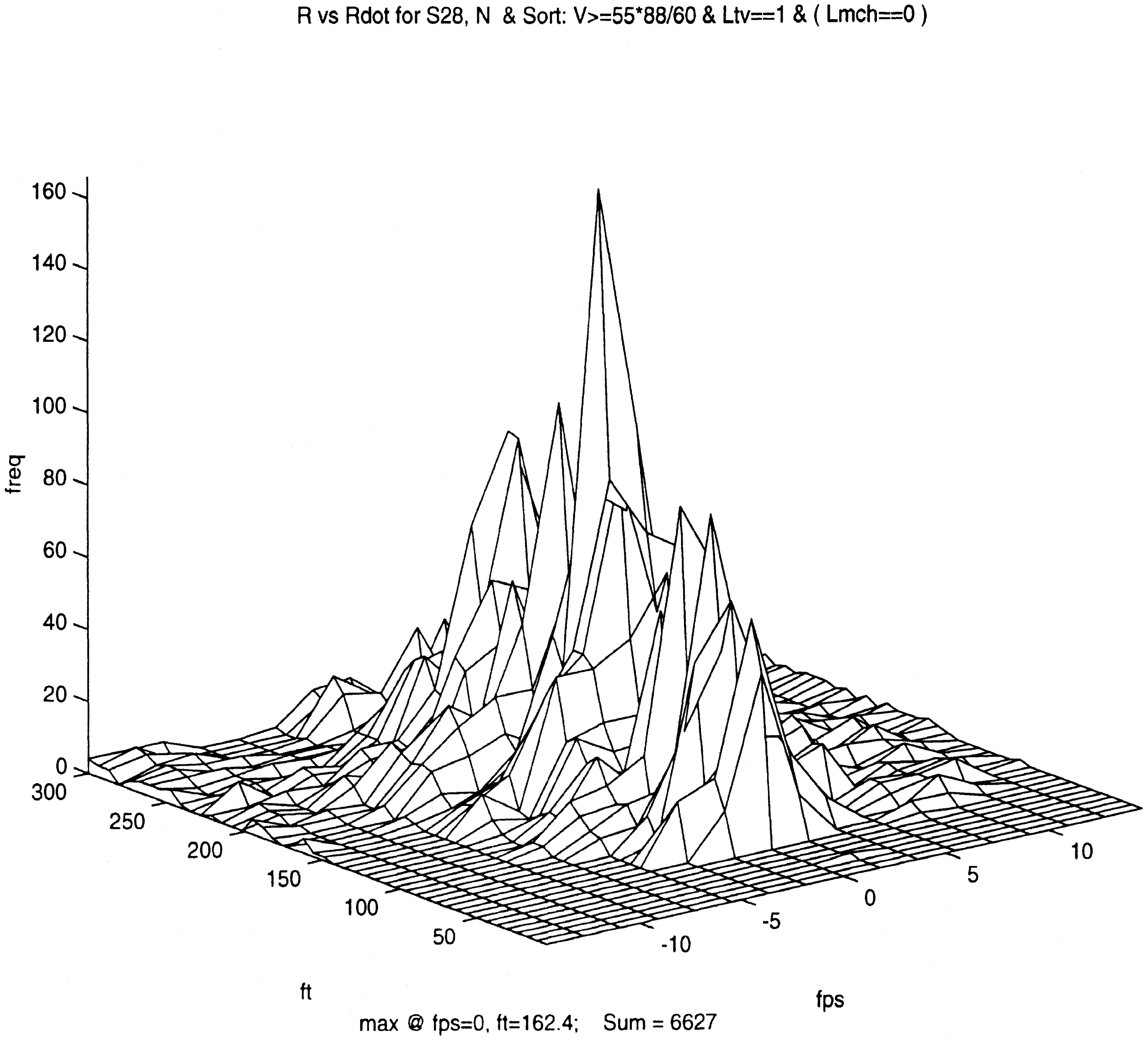


Figure A-29. Range vs. Range-Rate Histogram for Subject #29, Manual Driving.

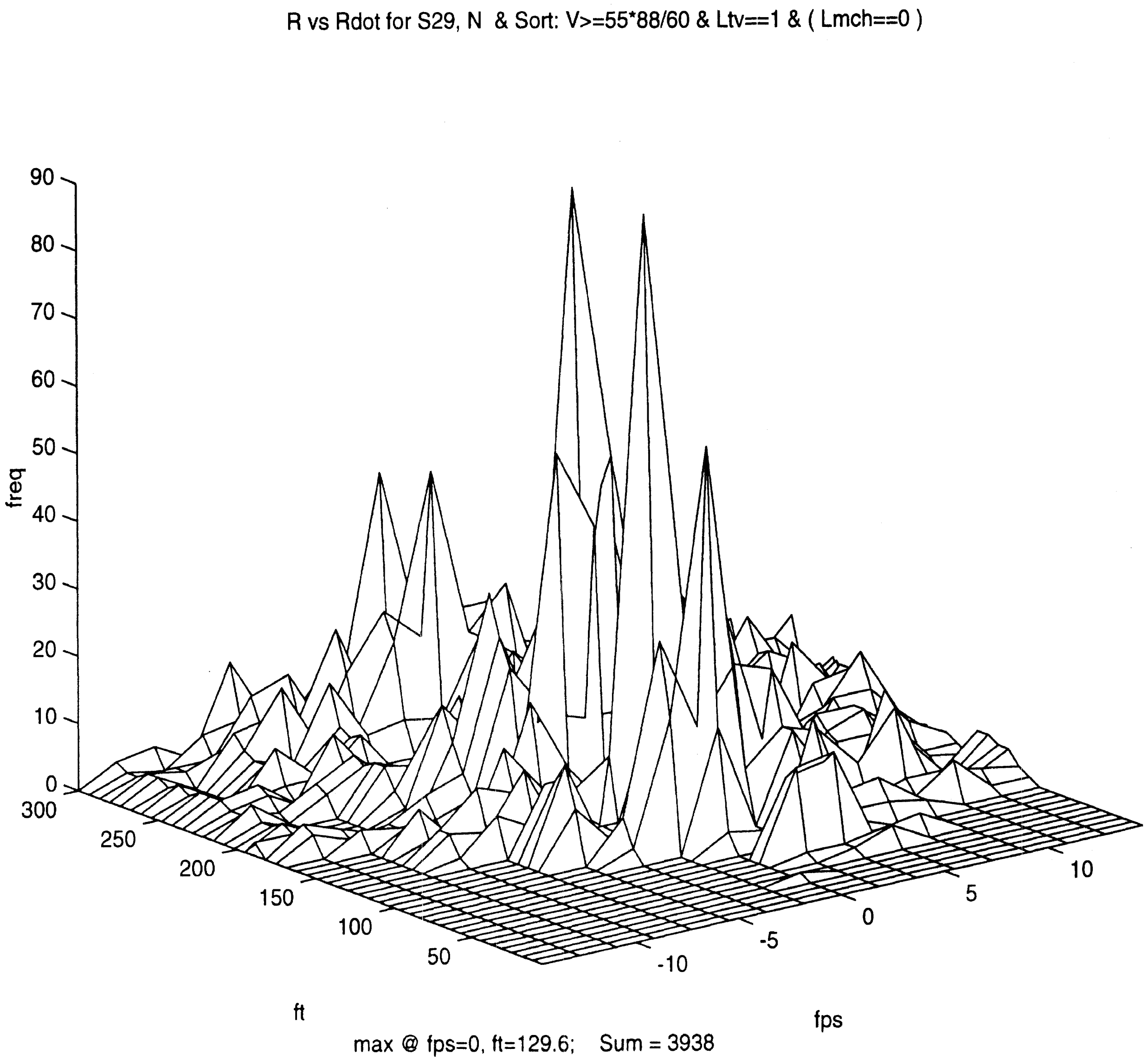


Figure A-30. Range vs. Range-Rate Histogram for Subject #30, Manual Driving.

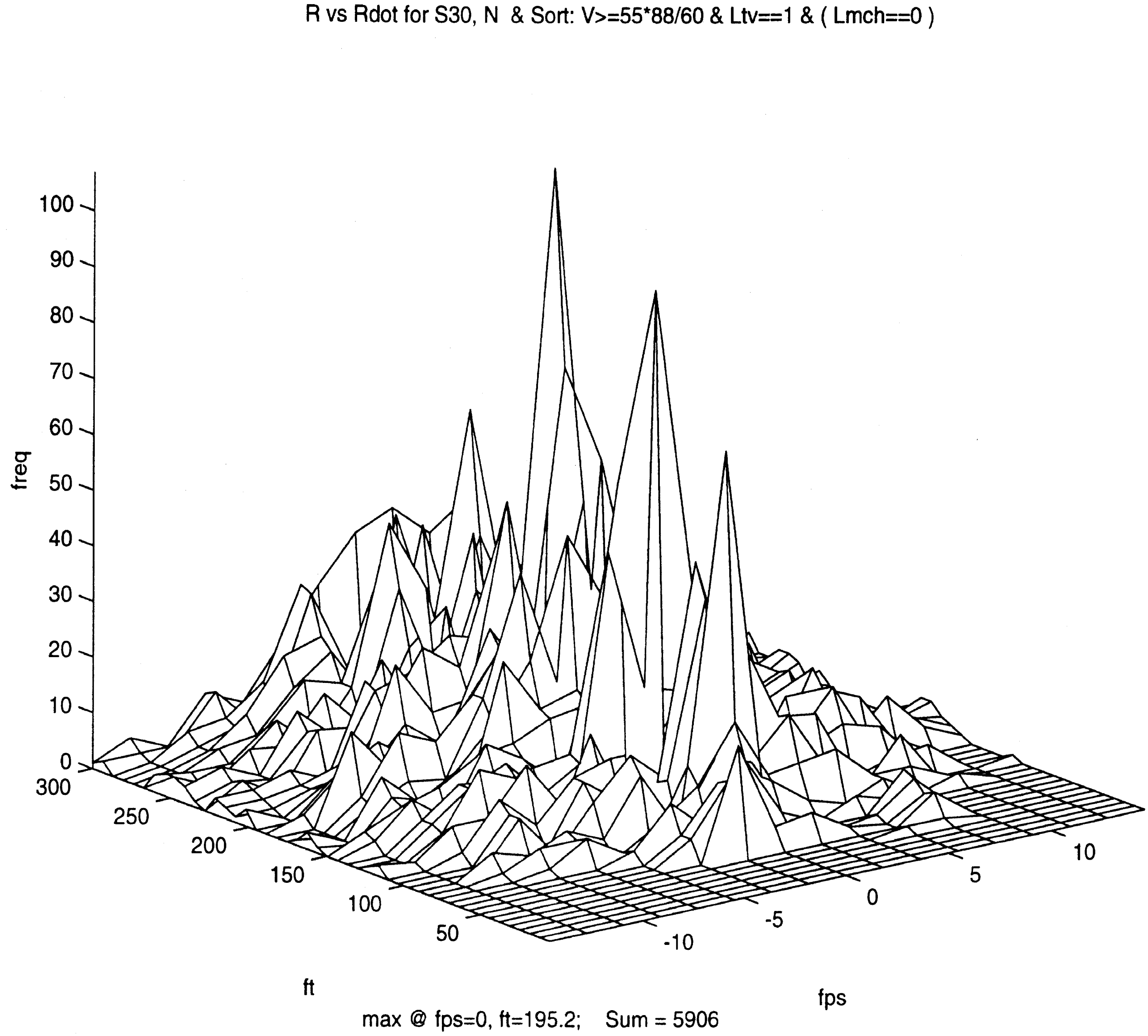


Figure A-31. Range vs. Range-Rate Histogram for Subject #31, Manual Driving.

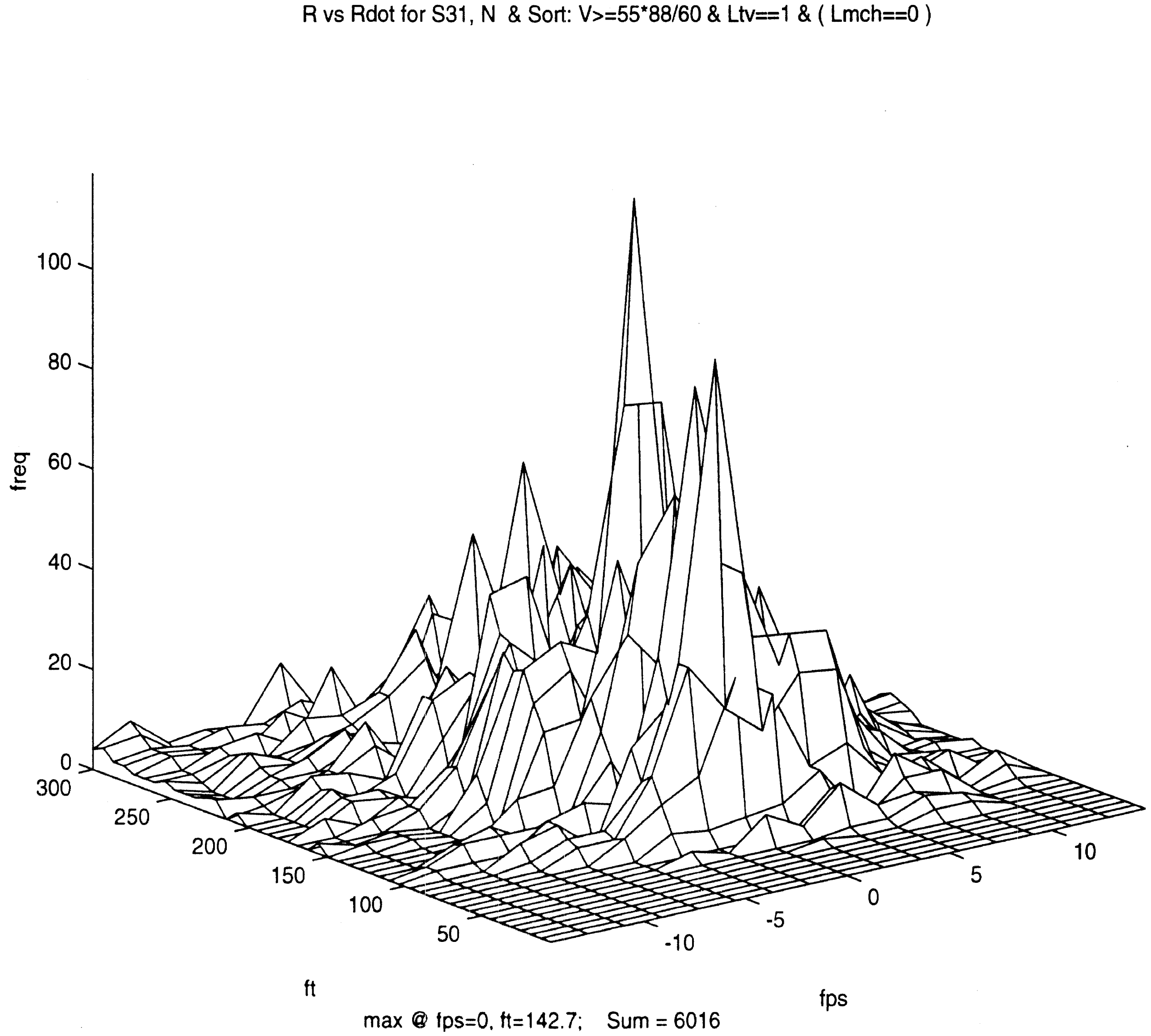
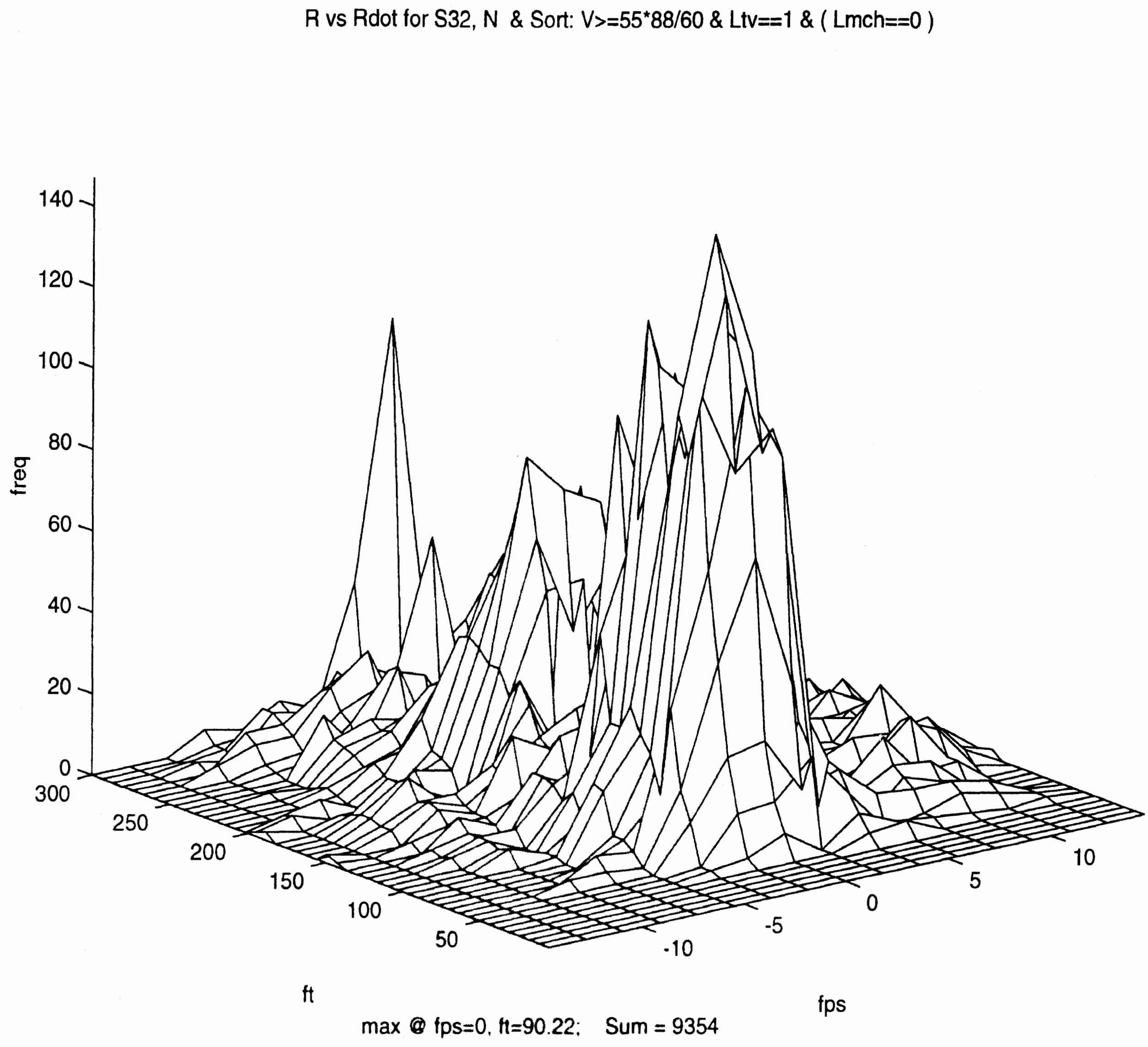


Figure A-32. Range vs. Range-Rate Histogram for Subject #32, Manual Driving.



R vs Rdot for S32, N & Sort: V>=55*88/60 & Ltv==1 & (Lmch==0)

max @ fps=0, ft=90.22; Sum = 9354

Figure A-33. Range vs. Range-Rate Histogram for Subject #33, Manual Driving.

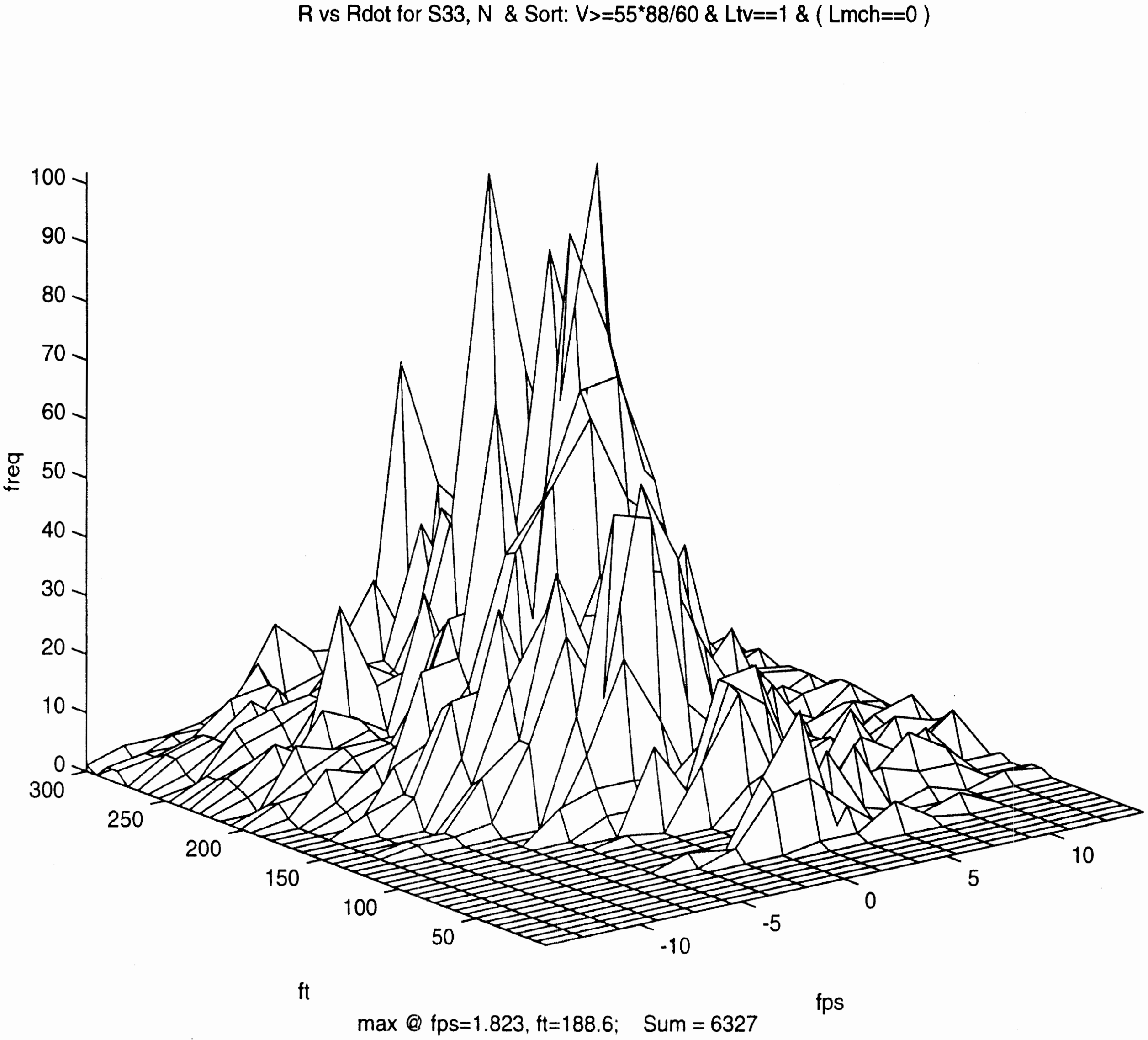


Figure A-34. Range vs. Range-Rate Histogram for Subject #34, Manual Driving.

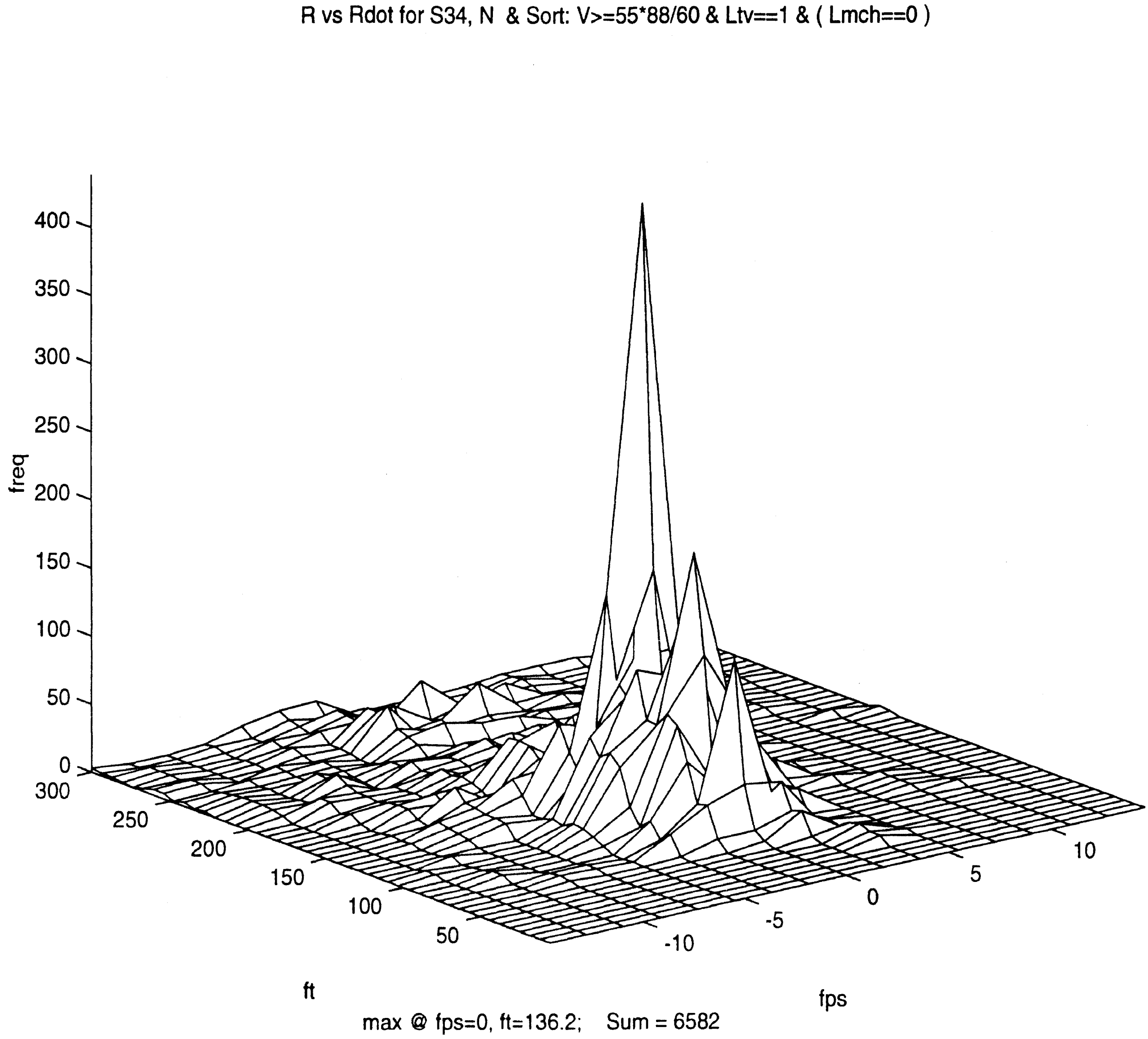


Figure A-35. Range vs. Range-Rate Histogram for Subject #35, Manual Driving.

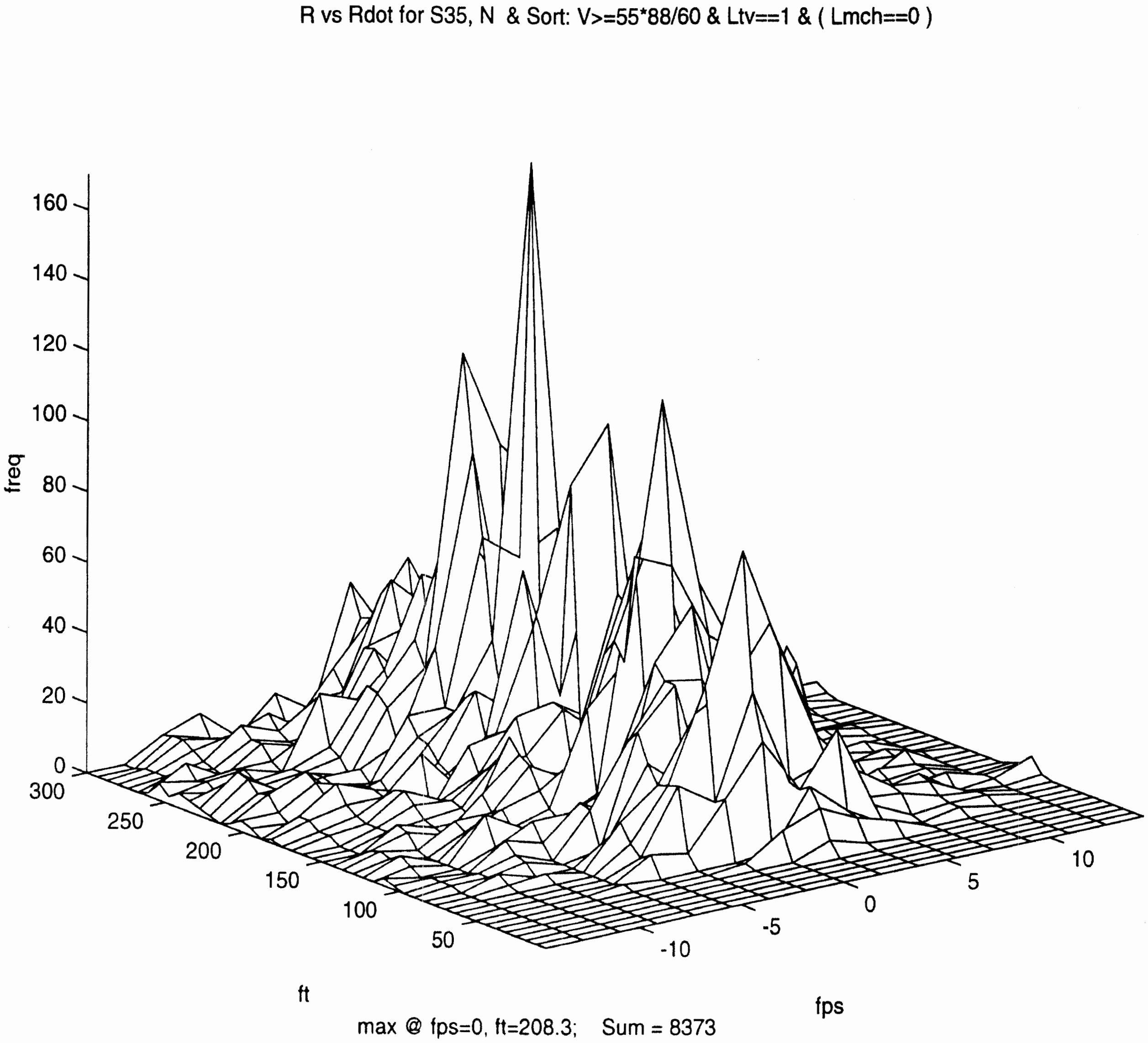


Figure A-36. Range vs. Range-Rate Histogram for Subject #36, Manual Driving.