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

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16. Abstract

The overall goal of the FOCAS program was to facilitate the development of a range of sensors and associated applications systems for commercial use that complement and supplement the forward crash-avoidance performance of drivers. To aid in progressing towards this goal, the program created tools, methodologies, and knowledge-bases as needed to expedite the development of adaptive cruise control (ACC) systems as well as systems providing forward collision warning (FCW) alerts. The results, findings, and conclusions of the program are numerous. The program was evolutionary both in terms of hardware and software advancements and more importantly understanding the drivers role in the application of this new technology. Prototype systems were used by lay persons in naturalistic driving. The culmination of the project resulted in a thorough analysis of five subject areas: (1) evaluation of ACC-with-braking, (2) braking latency, (3) development of a NHTSA warning algorithm, (4) evaluation of three FCW algorithms, and (5) research on vigilance as it relates to deceleration authority of an ACC system. The ACC systems developed in this study were well liked by drivers, convenient to use, and did not present any clear safety concerns.

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Autonomous intelligent cruise control, Longitudinal control, crash avoidance, Forward collision warning, adaptive cruise control, FCW, AICC, ICC, ACC	Unrestricted

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1.0 Executive Summary

The FOCAS program covered a five-year effort, involving several test configurations, research activities, and analysis methodologies that have yielded various results and recommendations concerning adaptive cruise control and forward collision warning systems. To facilitate ease of review, this Executive Summary is provided in tabular matrix formats as well as in a traditional narrative format. Each format covers the five years and their respective research elements. A vertical review, reviewing the scope of each individual topic over the full five years is presented first.

The work performed in the fifth year represents the culmination of research conducted in all five years. Hence, an examination of the research elements listed in the horizontal review for the fifth year provides an overview of progress achieved in developing a useful understanding of adaptive-cruise-control and forward-collision-warning systems.

Following the matrix form of tabular presentation, the executive summary has been extended to provide a synopsis of the FOCAS program in a narrative form.

1.1 Vertical Review

YEAR	ACC SYSTEM CONFIGURATION
1	• SAAB-based ACC system • Baseline ACC with 0.05 g decel from zero throttle coast down • Single fixed beam IR sensor • Fixed 1.4 second headway • Kinesthetic warning cue from automatic system decel.
2	• SAAB-based ACC system • ACC downshifting to get 0.1 g decel • Driver selectable headways added • Kinesthetic warning from transmission downshift • Audible warning from range-rate signal • Limited braking warning from low-decel signal • Volvo-based ACC with 0.18 g decel
3	• Chrysler Concorde-based ACC system • Sweep IR beam plus cut-in detection sensors in car grill. • Brake-by-wire braking system for 0.22 g decel • Headway and braking algorithm • Eight headway settings, from 0.6 to 2.0 seconds • Warning buzzer when system commands full 0.22 g braking

YEAR	ACC SYSTEM CONFIGURATION
4	• Basic system features are those developed in year 3 • Graduated braking applied when throttle modulation is not sufficient for controlling range and range-rate • ACC with various braking algorithms • Preceding vehicle deceleration considerations added to the braking algorithm
5	• Same configuration of ACC with braking as in the 4th year • Revised control algorithms for throttle and brake actuation • Improved acceleration response • Preceding vehicle deceleration used in the braking portion of the ACC algorithm • System with NHTSA warning concept • Time-to-impact warning system • System with desired-deceleration warning

YEAR	RESEARCH ACTIVITIES
1	• Freeway road testing using 36 subjects accompanied on three 55-mile drives • Driving comparisons for 3 modes - manual, conventional cruise control, and ACC based driving
2	• Test of 2 driver headway selection methods; 12 subjects over two 43-mile drives • Test of 3 different warning systems • Test of ACC system with braking • Extension of analytical bases for understanding ACC and crash-warning systems
3	• Developed a rule-based algorithm for the ACC system with braking • Developed warning feature with adjustable attention-getting thresholds • Incorporation of data acquisition system package from FOT program • Developed a new driver interface • Fourteen researchers test and evaluate the new system in five prescribed driving situations
4	• Developed graduated braking rules ("UMTRI algorithm") for maintaining ACC functionality • Proving grounds tests of ACC with braking • Studied driver intervention characteristics for use in designing ACC with braking
5	• Tested lay drivers using ACC with braking on freeways • Developed an experimental design for freeway testing using age and gender as independent variables • Tuned the braking algorithm to respond comfortably to rapid closing and/or preceding-vehicle braking • Developed procedures for studying braking latency • Developed procedures for identifying lane changes • Developed further the NHTSA collision-warning concept • Developed desired deceleration collision-warning concept • Developed further the time-to-impact collision-warning concept • Analyzed crash warning algorithms • Studied intervention vigilance and ACC deceleration authority

YEAR	ANALYSIS METHODOLOGY
1	• Assembled objective database of driving behavior in all modes • Assembled subjective database of driver responses to comfort and safety questions; ACC acceptance and comfort questions • Conducted focus group meetings to get additional driver feelings • Developed range-range rate diagram and histogram plot methodology
2	• Used objective database to classify drivers into hunters, gliders and followers • Tried neural network approach to defining different driving situations • Defined range-range rate histograms for each driver and driving class • Developed analytical basis for consideration of different warning cue types • Developed analytical basis for extension of ACC comfort and convenience to crash warning domain
3	• Extended braking rules and their implementation, considering safety, driver priority, driver compatibility, comfort and lack of ambiguity • Developed debriefing questionnaire to obtain subjective test results
4	• Examined test results for manual and ACC driving to study (1) driver headway time in manual driving, (2) when drivers choose to brake when closing, and (3) how much braking the driver decides to use • Studied looming coefficient, and braking target point • Developed "personalized algorithm", an adjustable controller to fit each driver's characteristics • Applied subjective ratings and evaluation of the ACC-with-braking system including preceding vehicle deceleration • Developed a computer model for simulating ACC performance. (Not exercised extensively in the 4th year)
5	• Conducted knowledge discovery in the ACC-with-braking database • Statistically analyzed for significance of test results • Processed FOT data to study braking latency and lane changing • Analyzed the NHTSA crash warning concept • Investigated different "data cleansing" methods for FCW • Evaluated various FCW algorithms • Studied FCW algorithms with respect to situation awareness • Analyzed intervention vigilance vs. ACC deceleration authority

YEAR	RESULTS
1	• ACC system performed well and drivers followed at safer distances, with reduced closing rates • Driver aggressiveness not defined by age, gender, or cruise control experience • Driving task difficulty varies significantly with driving mode • ACC driving mode is most orderly • Available reaction time is a significant performance measure
2	• Drivers prefer the adjustable headway feature; selection varies with age, but 1 to 2 seconds is good compromise • Drivers will prefer ACC with decel authority in the 0.1 to 0.2 g range • A three-stage driver warning system – downshifting, audible warning and brake-induced cue – can be considered for crash avoidance • Of 36 drivers, 8 are classified as hunters; 18 followers; and 10 gliders
3	• A system decel level of 0.22 g's is good for a high percent of headway conflicts on the highway • Drivers are quick to intervene at 0.22 g conflicts • Warning system is controversial; features need improvement • Algorithm has shortcomings in oscillations, smoothness, and brake delay • Resume accel level is unsatisfactory
4	• Invented interpolation rules for selecting level of braking • Created test procedures for use in proving ground situations • Subjective ratings indicate that lay driver felt comfortable with the ACC-with-braking system • The ACC/B algorithm using preceding vehicle deceleration was evaluated favorably
5	• Delivered database of ACC-with-braking measurements to NHTSA • Found statistically significant differences by age and gender among the lay test drivers • Found evidence of differences between manual and ACC driving • Completed report on braking latency and lane changing • Made discoveries concerning the influences of incorporating braking into ACC • Demonstrated that braking events are complex and multidimensional • Reported a NHTSA FCW algorithm for all inter vehicle relationships • Compared results on three FCW systems • Related vigilance requirements to deceleration authority

YEAR	FINDINGS AND RECOMMENDATIONS
1	• Revise ACC design to permit driver selectable headway; study selection method options • Add braking link to system to raise decel level to 0.1 g range • Improve performance of system on curves • Define analysis, simulation and test track methods for evaluating pre-deployment ACC's • Let drivers use ACC unaccompanied
2	• Enhance ACC test system to include braking for higher decel level • Enhance system ability to operate on curves • Additional warning system work based on time to impact, decel margin or reaction time margin • Improve system smoothness when braking is employed • Increase system utility by reducing situations where manual intervention is necessary
3	• Rules for generating velocity commands to be changed to get higher accel level • Braking algorithm to be modified to function more progressively • Limit range of adjustable headway settings to 1.0 to 2.0 seconds • Revise warning system buzzer to a less aggressive sound; consider second signal • Complete test using lay drivers • Focus on countermeasures to reduce exposure to risk
4	• Proving-grounds tests recommended for checking out vehicle and control system properties • Proving-grounds tests not generally recommended for determining driver interaction with ACC • Valid testing of ACC driving should be done on a freeway • A deceleration algorithm augmented to consider preceding vehicle braking was found to be satisfactory and it was recommended that the amount and timing of the response to braking be tuned to meet driver preferences
5	• ACC systems with braking will be enjoyable to use for most drivers • Development of collision-warning systems should consider that drivers brake for reasons of headway-time margin, closing rate, and preceding vehicle deceleration • Collision-warning systems must consider idiosyncrasies of the sensor • Research and development is needed for optimizing algorithms based on the NHTSA concept • Braking activity provides one indicator of a driver's situation awareness • The NHTSA FCW algorithm tends toward a request for emergency action • The Ttc warning is primarily a situation awareness prompt • The VcDot algorithm combines both situation awareness and emergency concerns • ACC-with-braking will provide a reduction in the workload associated with headway-keeping

1.2 Horizontal Review

YEAR	ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	RECOMMEN-DATIONS
1	• SAAB-based ACC system • Baseline ACC with 0.05 g decel from zero throttle coast down • Single fixed beam IR sensor • Fixed 1.4 second headway • Kinesthetic warning cue from automatic system decel.	• Freeway road testing using 36 subjects accompanied on three 55-mile drives • Driving comparisons for 3 modes - manual, conventional cruise control and ACC based driving	• Assembled objective database of driving behavior in all modes • Assembled subjective database of driver responses to comfort and safety questions; ACC acceptance and comfort questions • Conducted Focus group meetings to get additional driver feelings • Developed range-range rate diagram and histogram plot methodology	• ACC system performed well – drivers followed at safer distances, with reduced closing rates • Driver aggressive-ness not defined by age, gender or cruise control user experience • Driving task difficulty varies significantly with driving mode • ACC driving mode is most orderly • Available reaction time is a significant performance measure	• Revise ACC design to permit driver selectable headway; study selection method options • Add braking link to system to raise decel level to 0.1 g range • Improve performance of system on curves • Define analysis, simulation and test track methods for evaluating pre-deployment ACC's • Let drivers use ACC unaccompanied
2	• SAAB-based ACC system • ACC downshifting to get 0.1 g decel • Driver selectable headways added • Kinesthetic warning from transmission downshift • Audible warning from range-rate signal • Limited braking warning from low-decel signal • Volvo-based ACC with 0.18 g decel	• Test of 2 driver headway selection methods; 12 subjects over two 43-mile drives • Test of 3 different warning systems • Test of ACC system with braking • Extension of analytical bases for understanding ACC and crash warning systems	• Used objective database to classify drivers into hunters, gliders and followers • Tried neural network approach to defining different driving situations • Defined range-range rate histograms for each driver and driving class • Developed analytical basis for consideration of different warning cue types • Developed analytical basis for extension of ACC comfort and convenience to crash warning domain	• Drivers prefer the adjustable headway feature; selection varies with age, but 1 to 2 seconds is good compromise • Drivers will prefer ACC with decel authority in the 0.1 to 0.2 g range • A 3-stage driver warning system – downshifting, audible warning and brake-induced cue – can be considered for crash avoidance • Of 36 drivers, 8 are classified as hunters; 18 followers; and 10 gliders	• Enhance ACC test system to include braking for higher decel level • Enhance system ability to operate on curves • Additional warning system work based on time to impact, decel margin or reaction time margin • Improve system smoothness when braking is employed • Increase system utility by reducing situations where manual intervention is necessary

YEAR	ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	RECOMMEN-DATIONS
3	• Chrysler Concorde-based ACC system • Sweep IR beam plus cut-in detection sensors in car grill • Brake-by-wire braking system for 0.22 g decel • Headway and braking algorithm • Eight headway settings, from 0.6 to 2.0 seconds • Warning buzzer when system commands full 0.22 g braking	• Development of a rule-based algorithm for ACC system with braking • Development of warning feature with adjustable attention-getting thresholds • Incorporation of data acquisition system from FOT program • Development of a new driver interface • Fourteen researchers test and evaluation of the new system in five prescribed driving situations	• Extended braking rules and their implementation, considering safety, driver priority, driver compatibility, comfort and lack of ambiguity • Developed debriefing questionnaire to obtain subjective test results	• A system decel level of 0.22 g's is good for a high percent of headway conflicts on the highway • Drivers are quick to intervene at 0.22 g conflicts • Warning system is controversial; features need improvement • Algorithm has shortcomings in oscillations, smoothness and brake delay • Resume accel level is unsatisfactory	• Rules for generating velocity commands to be changed to get higher accel level • Braking algorithm to be modified to function more progressively • Limit range of adjustable headway settings to 1.0 to 2.0 seconds • Revise warning system buzzer to a less aggressive sound; consider second signal • Complete test using lay drivers • Focus on countermeasures to reduce exposure to risk
4	• Basic system features are those developed in year 3 • Graduated braking applied when throttle modulation is not sufficient for controlling range and range-rate • ACC with various braking algorithms • Preceding vehicle deceleration considerations added to the braking algorithm	• Development of graduated braking rules ("UMTRI algorithm") for maintaining ACC functionality • Proving grounds tests of ACC with braking • Study of driver intervention characteristics for use in designing ACC with braking	• Examined test results for manual and ACC driving to study (1) driver headway time in manual driving, (2) when do drivers brake while closing, and (3) how much braking the driver decides to uses • Studied looming coefficient and braking target point • Developed personalized algorithm, an adjustable controller to fit each driver's characteristics • Applied subjective ratings and evaluation of the ACC-with-braking system including preceding vehicle deceleration • Developed a computer model for simulating ACC performance	• Invented interpolation rules for selecting level of braking • Created test procedures for use in proving ground situations • Subjective ratings indicate that lay driver felt comfortable with the ACC-with-braking system	• Proving-grounds tests recommended for checking out vehicle and control system properties • Proving-grounds tests not generally recommended for determining driver interaction with ACC • Valid testing of ACC driving should be done on a freeway A deceleration algorithm augmented to consider preceding vehicle braking was found to be satisfactory and it was recommended that the amount and timing of the response to braking be tuned to meet driver preferences

YEAR	ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	RECOMMEN-DATIONS
5	• Same configuration of ACC with braking as in the 4th year • Revised control algorithms for throttle and brake actuation • Improved acceleration response • Preceding vehicle deceleration used in the braking portion of the ACC algorithm • System with NHTSA warning concept • Time-to-impact warning system • System with desired-deceleration warning •	• Tested lay drivers using ACC with braking on freeways • Developed an experimental design for freeway testing using age and gender as independent variables • Tuned the braking algorithm to respond comfortably to rapid closing and/or preceding-vehicle braking • Developed procedures for studying braking latency • Developed procedures for identifying lane changes • Developed further the NHTSA collision-warning concept • Developed desired deceleration collision-warning concept • Developed further the time-to-impact collision-warning concept • Analyzed crash warning algorithms • Studied intervention vigilance and ACC deceleration authority	• Conducted knowledge discovery in the ACC-with-braking database • Statistically analyzed for significance of test results • Processed FOT data to study braking latency and lane changing • Analyzed the NHTSA crash warning concept • Investigated different "data cleansing" methods for FCW • Evaluated various FCW algorithms • Studied FCW algorithms with respect to situation awareness • Analyzed intervention vigilance vs. ACC deceleration authority	• Delivered database of ACC-with-braking measurements to NHTSA • Found statistically sig. differences by age and gender among the lay test drivers • Found evidence of differences between manual and ACC driving • Completed report on braking latency and lane changing • Made discoveries concerning the influences of incorporating braking into ACC • Demonstrated that braking events are complex and multidimensional • Reported a NHTSA FCW algorithm for all inter-vehicles relationships • Compared results on three FCW systems • Related vigilance requirements to deceleration authority	• ACC systems with braking will be enjoyable to use for most drivers • Development of collision-warning systems should consider that drivers brake for reasons of headway-time margin, closing rate, and preceding vehicle deceleration • Collision-warning systems must consider idiosyncrasies of the sensor • Research and development is needed for optimizing algorithms based on the NHTSA concept • Braking activity provides one indicator of a driver's situation awareness • The NHTSA FCW algorithm tends toward a request for emergency action • The Ttc warning is primarily a situation awareness prompt • The VcDot algorithm combines both situation awareness and emergency concerns • ACC-with-braking will provide a reduction in the workload associated with headway-keeping

1.3 Synopsis of the FOCAS Program

The overall goal of the FOCAS program is to facilitate the development of a range of commercialize-able systems that complement and supplement the forward crash-avoidance performance of drivers. To aid in progressing towards this goal, the program has created

- adaptive cruise control (ACC) systems
- systems for providing forward collision-warning (FCW) alerts
- procedures for evaluating the performance of these systems
- analysis methodologies
- databases of results from driver controlled tests
- basic knowledge concerning manual driving

Over the five-year span of this cooperative project, UMTRI integrated components to create working ACC systems, developed algorithms for performing ACC control functions and for providing FCW alerts, and conducted testing and analysis procedures. This has lead to quantitative results and conceptual ideas pertaining to human-centered design of driver assistance systems.

UMTRI's partners at Automotive Distance Control Systems (ADC) and Conti-Teves provided sensors, communication and computation subsystems, and braking actuators. These partners plus Haugen Associates and the State of Michigan, along with research direction and support from NHTSA, formed an effective partnership. The partnership was able to combine its talents and resources in an efficient manner, thereby producing results that otherwise would not have been attained if the partners had been acting individually.

Three annual reports, one for each of the first three years, were delivered. These reports covered research and development activities pertaining to a progression of increasingly capable ACC systems and initial studies of driver alert and warning concepts. The initial ACC system that was employed in highway driving by lay drivers consisted of a fixed beam sensor installed in a SAAB 9000 vehicle. In the second and third years, this system was refined through the addition of a swept beam sensor to provide better performance on curves, transmission downshifting to increase deceleration authority, driver adjustable values of headway time, and finally a smart brake booster to allow electronic control of braking. The new and enhanced ACC configuration was installed and operated in a Chrysler Concorde by the end of the third year.

Objective and subjective results based upon the driving behavior of 36 laypersons operating the first ACC system on freeways showed that the ACC design concepts used in the FOCAS program were satisfactory. Objective measurements showed that this ACC system was capable of meeting its functional purpose (controlling speed and distance relative to a preceding vehicle) in a highway environment. Subjective ratings, interviews, and discussions in focus groups indicated that drivers enjoyed operating the system. They felt comfortable using the initial system, regardless of its limitations. These initial results provided evidence that the ACC concepts, as developed in the FOCAS program, have real world viability. In essence, proof of concept was demonstrated early in the program.

This document contains a concise description of pertinent research and development activities conducted in the first three years of the program. Further details concerning those activities are presented in the annual reports prepared by UMTRI. However, the main emphasis of this final report concerns the results and findings generated in the remaining years of the FOCAS program.

The research activities during the fourth year were primarily focused on questions associated with employing the foundation brakes in an ACC system. An automatic braking capability was available in an experimental vehicle at the end of the third year. However, the specific form of braking algorithm to use, and the parametric choices that go with it, were not established until into the fifth year of the program.

The basis for performing highway driving with laypersons operating ACC-with-braking was developed in the fourth year. Test-track experiments with lay persons operating various adjustable types of ACC-with-braking systems were conducted. The drivers indicated that they would be comfortable operating these systems in highway driving. The researchers determined that some drivers behave very conservatively in a test-track environment although most drivers appear to behave normally. Hence, it does not appear that representative results can be obtained from test-track experiments. Nevertheless, the results indicated to the researchers that highway driving with ACC-with-braking systems, similar to those used in the test track experiments, would be a reasonable activity. The test-track activities provided the evidence needed to apply for human use approval for on-road driving with the ACC-with-braking system.

The research activities performed after the fourth year addressed five major research tasks that were deemed important in developing concluding results and findings that would have current and long-range applicability and utility. Brief summaries of these tasks are as follows:

1) Evaluation of ACC-with-braking (Freeway driving with lay drivers)

The objectives of this research task were:

a) Evaluate the operational performance of a basic ACC-with-braking function in freeway driving. (The chosen system had a deceleration authority of 0.22g.)
b) Identify how results from driving with the ACC-with-braking system differs from results obtained in the ICC FOT project, which employed an ACC system with approximately 0.07 g of deceleration authority.
c) Examine operational performance issues associated with braking capability as implemented in our ACC-with-braking function.

In pursuit of these objectives, pertinent findings were derived from examination and evaluation of the behavior of 24 laypersons operating the ACC-with-braking system on freeways. The experimental design for this task involved a randomly selected sample of drivers from differing age groups and gender. These drivers had experience with conventional cruise control. The following issues were addressed:

1. Achievement of functional goals concerning speed and distance-keeping performance as well as brake timing and magnitude
2. Influence of accompanied (researcher present) driving on manual driving behavior
3. Driving situations occurring when the ACC system is braking
4. Driver decisions with regard to manual brake interventions on ACC-with-braking

(There is a special table included at the beginning of this executive summary. This table provides a summary of the overall project in a matrix format designed to facilitate review of selected aspects of the project. Additional information concerning the issues listed above is presented in the sections of the table pertaining to year 5.)

2) Braking latency

During the fifth year, two special studies were identified and prescribed. These studies involved processing ICC FOT data to examine braking latency and driver lane changing behavior. A separate, detailed report on these subjects was written and delivered to NHTSA. Certain results from the study of braking latency are reported here. These results provide information on situations in which both the preceding and equipped vehicles decelerated at levels greater than 0.1 g. The data from these situations were employed in evaluating forward crash warning algorithms as indicated in the description of task 4).

3) NHTSA's warning algorithm

This task involved analyzing a crash-warning algorithm that is of special interest to NHTSA. The warning issued by this algorithm calls for emergency braking upon the part of the driver. Different methods of programming the algorithm were studied. The influences of sensor characteristics were investigated. A Kalman filter approach was developed and used in the final version of the warning algorithm. This final report provides documentation on the specific algorithm developed in this task.

4) Evaluation of FCW systems

Three different types of FCW systems were examined in this task. ICC FOT data were employed as inputs to the respective algorithms. The names and types of FCW systems are as follows: (The algorithms used in studying these FCW systems were created and prepared by UMTRI for the FOCAS program.)

- NHTSA algorithm - This has an emergency braking goal.
- Tti algorithm - This has a situation awareness goal.
- Vcdot algorithm - This has both situation awareness and crash avoidance aspects.

The results provide insights into when these different types of FCW systems would warn the driver.

5) Vigilance versus deceleration authority

Finally, an analysis of ICC FOT cases of driver braking intervention was performed as a means of estimating the influence of ACC deceleration authority on the frequency of brake intervention and, by implication, the potential for lapses in driver vigilance over long periods of sustained ACC engagement.

Each of these five tasks produced detailed results that are reported in the body of this report. These results along with the overall understanding developed in the FOCAS program have led to a broad appreciation of certain aspects of human-centered design. These aspects range from system development concepts to specific system characteristics that drivers have rated favorably. They are based upon a theme of comparing ACC driving to manual driving. To the extent possible in the FOCAS program, any ACC driving experience was accompanied by similar manual driving on the same roads with the same basic vehicle.

Although not as well developed as the ACC procedures, collision-warning studies involving comparisons between when drivers brake or intervene manually and when they would be alerted by a particular FCW system were performed.

In particular with regard to designing and evaluating specific ACC systems, a hierarchy of design considerations has evolved from the process of creatively engineering new systems and then scientifically evaluating them. These considerations, ordered by the level of abstraction involved, run from functional purpose to physical form as indicated by the following sequence of elements:

1) Functional purpose (objectives)
2) Functional concept
3) Functional form
4) Component engineering
5) Physical form (reality)

To complete a unified design, each of these five elements needs to fit with the others. Since a theory or science of driving is in its beginning stages (particularly, as applicable to driver assistance systems), the evaluation process involves on-road driving. The purpose of the on-road driving is to see if system performance and driver behavior and subjective ratings tend to confirm that the effects observed and discovered are in keeping with the goals desired. Generally, the evaluation process involves considering each of these five items from a critical perspective, looking for unwanted effects as well as proof of concept.

With respect to verifying the viability of an ACC system at the highest levels of abstraction, a two-dimensional histogram displaying observed system performance is very useful. In the histogram, the frequency of driving occurrence is displayed as a function of normalized headway time and range rate (relative velocity between the ACC vehicle and its preceding vehicle). If the observed headway time is usually very close to the desired headway time set by the driver (that is, normalized headway time is close to 1.0), the system is performing well in terms of distance control. In addition, if the range rate is nearly zero (that is, both vehicles are traveling at the same speed), the system is performing well in terms of speed control. For example, results for the FOCAS ACC-with–braking system show that the most likely value of headway time and range rate occurs at the desired headway time with range rate equal to zero. Furthermore, the frequency of occurrence of the most likely value for ACC operation is approximately five times larger than that obtain in manual driving. As simple as it may seem in hindsight, this method for displaying on-road observations for both ACC and manual driving appears to have contributed immensely to the understanding required to convince engineers and scientists that ACC systems work.

At a less abstract level, the functional form of the FOCAS ACC systems has been compared to the manner in which people drive manually. Examination and interpretation of manual driving data indicates that individual drivers have distinct preferences with respect to headway time. The initial ACC system had only one headway time setting at 1.4 seconds. (At the time, this was characterized as the longest setting that we could use without receiving a host of driver complaints.) Subsequent research showed that a range of selectable headway times from 1 to 2 seconds was needed to satisfy the great majority of drivers. However, the manual driving data indicated that the most likely value of headway time in manual driving was less than 1.0 seconds for many drivers. In the interest of promoting safer following distances, various standards setting organizations are advocating a minimum setting of 1.0 seconds. Interestingly, the FOCAS data indicate that even with a 1.0 second minimum-headway time, the FOCAS ACC system achieves nearly the same average headway time as that achieved in manual driving. The ACC system appears to follow as closely on average but without as much tailgating. Test results indicate that, during manual driving on freeways, 14 percent of the driving time is at headway times less than 0.8 seconds. In ACC driving, the comparable frequency is 4 percent of the time.

In a behavioral sense, drivers may be characterized by their tendencies in following distance (or headway time margin) and speed. In ACC systems, drivers express their preferences through adjusting their set speed and desired headway time. In the FOCAS program and in companion research in the ICC FOT, comparisons have been made between distance and speed performance in manual and ACC driving for individual drivers.

During the FOCAS program, the looming effect caused by objects approaching the human eye has been employed in explaining observations of driver behavior. Conceptual reasoning has been used to relate driver perception of the looming effect to basic headway control variables. These variables have been named headway time margin (Htm = range divide by velocity) and time to impact (Tti = range divided by the absolute value of range rate when range rate is negative). The time to impact (Tti) is a measure of the closing rate with regard to an impeding vehicle. The headway time margin (Htm) is a measure of the headway time between two vehicles that are proceeding at approximately the same speed. These two quantities (Htm and Tti) along with a perception of velocity provide the driver with information concerning the driving situation. This information is comparable to that provided by the sensors in the ACC system. The point is that a sense of the human-centered qualities of an ACC design can be developed by expressing ACC system characteristics in terms of Htm and Tti.

Examination of the FOCAS data and results indicates that ACC systems that have a range of headway time settings from 1 to 2 seconds, thereby providing Htm values falling in this range, will be well received by most drivers. In the context of this study, this range of settings provides a human-centered range of headway options.

With regard to Tti, examination of FOCAS data and results indicates that many drivers tend to feel stress (because of the looming effect) when Tti falls below 10 seconds. A nominal range of closing rates for ACC systems appears to be in the range from 10 to 12 seconds. The time constant chosen for closing in the FOCAS ACC systems was 11 seconds. Subjective ratings indicated that drivers were satisfied with the performance of these systems in closing situations approaching constant-speed following conditions. Furthermore in manual driving, data on closing performance was often characterized by closing rates at or above that associated with an 11-second time constant. Hence, ACC systems that tend to close in a manner resembling an 11-second time constant are considered to have a human-centered quality that provides the driver with confidence. In this sense, the ACC system is operating in a manner that does not conflict with the driver's skills as learned through experience in driving manually.

Further conceptual work in the FOCAS program has led to broad design concepts for driver assistance systems. These concepts are compatible with psychological ideas associated with mental activities involving knowledge-based, rule-based, and skill-based behavior. In ACC systems, strategy and knowledge-based behavior is still left primarily to the driver. (If the driver thinks that more braking is needed, the driver should brake.) Based on ideas corresponding to the nature of rule-based and skill-based human behavior, design approaches involving non-linear control ideas associated with sliding surfaces have been employed. This activity has led to generalized approaches, describing functional concepts, functional forms, and component engineering applicable to human-centered design of ACC systems.

Efforts toward the end of the FOCAS program were directed at exploring the braking performance associated with ACC systems and matters associated with forward collision warning and rear-end crash avoidance.

The results indicate that the braking rules employed in the ACC-with-braking algorithm were acceptable to drivers. Drivers are sensitive to small changes in deceleration if they are sudden. For example, simply dropping the throttle will alert most drivers and passengers and cause them to bring their attention to the forward scene. If drivers feel that they have been jerked unnecessarily, they will be unhappy. In order to accommodate this in ACC system design, the systems used in the FOCAS program incorporated restrictions into their braking rules. These restrictions include the following items. Do not brake if range rate is positive (when the vehicles are separating). Limit the jerk (deceleration rate) to 0.06 g per second. And, constrain the deceleration commands to fall in the range from 0.07 g to 0.22 g depending upon a compromise between desired headway-time for ACC purposes and a tolerable transient headway-time-margin, given that the current situation warrants braking.

The specified range of deceleration reflects two observations. First, typical passenger cars can coast-down at approximately 0.04 to 0.05 g. and drivers do not wish the ACC system to brake in situations where coasting will suffice. With regard to the 0.22g limit, freeway data show that 0.22 g is adequate to handle all but a few isolated incidents. The driver is responsible for avoiding crashes (crash avoidance is not a functional purpose of the ACC system). In this sense, the maximum deceleration authority of the ACC system is somehow related to the transition from ACC functionality to forward collision warning and perhaps to active crash-avoidance systems.

The FOCAS program has provided data that allow us to investigate the timing of when drivers decide to brake as well as the amount of braking they decide to use. This research is in its beginning stages. Braking serves so many purposes that it can be difficult to distinguish discretionary braking from necessary braking. (If only we could record the driver's thoughts and perceptions.) FOCAS results indicate that the reasons for many of the braking cases, which are considered necessary, appear to be characterized by short headway-time-margin, short time-to-collision, or rapid deceleration of an impeding vehicle. Unfortunately, we have not discovered a single measure or intersecting sets of measures that appear to account for the onset time of most of the necessary brake events.

The cumulative distributions of measured values of headway-time-margin at the time of brake application are similar for ACC-with-braking and manual driving at headway time margins below 0.8 seconds. This constitutes about 40 percent of the brake applications associated with either ACC or manual driving in the FOCAS project. Above 0.8 seconds, the distribution for ACC braking increases rapidly to approximately 100 percent at 2.0 seconds. This is as expected because the maximum headway-time setting for the ACC system was 2 seconds and the ACC system does not perform discretionary braking. The basic reason for ACC braking is to slow the vehicle until throttle modulation can achieve the desired headway time.

Interestingly, the distribution of headway time for manual brake interventions on ACC driving indicates that drivers decide to intervene on ACC before close following becomes stressful. Most of these interventions are discretionary. Apparently, drivers can usually anticipate the need for intervention well before the situation becomes critical compared to when manual and ACC braking typically occur.

The results for time-to-collision have some characteristics that are similar to those just described for headway-time-margin. The cumulative distributions of time-to-collision at the time of brake application are similar for ACC and manual driving up to a time-to-collision of approximately 8 seconds. Above 8 seconds ACC braking increases more rapidly arriving at about 80 percent at Tti = 20 seconds compared to a manual value of about 60 percent at Tti = 20 seconds. However, manual interventions on ACC driving occur frequently at levels of Tti less than 8 seconds. (Manual braking interventions terminate ACC driving.) The results indicate that the cumulative distributions for ACC braking and manual brake interventions on ACC are equal at a Tti value of approximately 11 seconds, which corresponds to approximately 40 percent of each distribution. This indicates that the closing situation is often stressful when drivers intervene on ACC-with-braking. Their abilities to anticipate problems do not appear to allow them to act before the situation becomes more stressful than that typically exhibited by ACC driving.

Further insight is provided by examining the deceleration employed during braking events. The observed results indicate that the peak deceleration during intervention events is much more likely to be larger than that for ACC or manual driving for decelerations above 0.15 g. This indicates that those intervention events are more likely to be severe events, which is as expected. However, the distribution of braking level formed by combining the intervention cases with the ACC braking cases is nearly identical to the manual braking distribution above 0.15 g of deceleration. (Even at lower levels of deceleration, the two distributions are similar.) These results appear to indicate that, in the driving environment encountered in the FOCAS study, drivers wanted certain levels of deceleration. If the ACC system did not provide what they wanted, drivers intervened to get the deceleration they wanted. These results indicate that, in general, if drivers wanted more braking, they applied it. Nevertheless, the amount of data gathered here is not believed to be sufficient to reach conclusions about the extreme tails of the distributions as they relate to crashes and emergency crash-avoidance situations, which drivers are expected to handle.

The human-centered concepts that emerged from studying the braking aspects of ACC-with-braking were used in structuring the examination of three types of forward collision warning (FCW) systems in the FOCAS program.

The Tti algorithm for FCW used a nominal threshold value of Tti = 10 seconds to provide the driver with a warning when the driving situation would appear stressful to the driver due to the looming effect. Limited experience using this algorithm on the road indicated that individual drivers might have distinct preferences concerning their threshold value. (If given the choice, it is estimated that drivers might be expected to pick threshold values ranging from 6 to 14 seconds.) From a human-centered perspective, the purpose of the Tti algorithm was to alert the driver when the driving situation was such that the driver would normally act to change it. In this sense, the Tti algorithm provides a situation-awareness alert in situations that are expected to be stressful to the driver.

The Vcdot algorithm was based upon the level of deceleration needed to return to a desired headway time. In a manner similar to that used in ACC systems, a deceleration command Vcdot was calculated from the existing values measured for range, range rate, and velocity. The driver was warned when this command exceeded a particular threshold value. Based on analyses of situations, in which drivers applied braking, a nominal value of 0.4 g was selected for use in studying this algorithm. This algorithm was aimed at warning drivers before an extreme emergency occurred. In a sense, it indicated that the action needed to re-establish headway time is well beyond what ACC systems or drivers would normally be expected to do.

The NHTSA algorithm is based upon emergency braking considerations. Provision is made to account for a driver reaction delay of 1.5 seconds followed by braking that achieves a deceleration of 0.75g. Given these parameters, the minimum range needed to avoid a crash is computed. If the existing range is less than the computed minimum range, a warning is issued. To be able to predict more than 1.5 seconds into the future means that very good, clean sensor data is needed to implement the NHTSA algorithm successfully. In this regard, the sensor requirements for FCW and crash avoidance are much more demanding than the requirements needed to implement ACC successfully.

Results, obtained by exercising the algorithms using data measured during manual braking events, showed that the three warning algorithms differ greatly with respect to frequency of warning and the time-to-impact at the time of warning. In 303 cases where both the preceding and following vehicle decelerated at more than 0.1g from initial speeds greater than 50 mph (80 kph), the NHTSA algorithm would have warned in 20 of these cases. The Vcdot algorithm would have warned in 78 of these cases whereas the Tti algorithm would have alerted the driver in 201 of these cases. If provisions were made to prevent warning if the driver is already braking, the results would change to 1 case for NHTSA, 16 cases for Vcdot, and 55 cases for Tti. Clearly, such provision would eliminate many nuisance alarms.

The fiftieth percentile values of time-to-impact for these warning systems (including warnings when the driver is already braking) are 2.5, 5.5, and 8.5 seconds for the NHTSA, Vcdot, and Tti algorithms respectively. This spread in Tti values is to be expected given the underlying warning concepts. However, these results indicate that the NHTSA and Vcdot algorithms will not warn in many cases where one would expect that drivers would feel stress and would be frightened. This implies that perhaps many drivers will feel that crash warning systems that tend to emphasize emergency events are not performing to their satisfaction. This observation indicates that research aimed at finding out how drivers will use warning systems in on-road situations is needed. Successful human-centered design of FCW systems depends upon understanding how drivers will react and use warnings in their driving environment.

With regard to reducing accident risks below those associated with manual driving now, the study concludes that driver assistance systems (ACC and FCW) should be tailored to the mental and physical capabilities of drivers, including their ability to remain vigilant. A better understanding of the knowledge-based cognitive abilities of drivers is needed to address issues such as the maximum deceleration of ACC systems and the severity of closing situations at which FCW systems should warn. Future progress toward reducing exposure to risk, avoiding crashes, and reducing the severity of injury depends upon developing fundamental knowledge pertaining to when drivers decide to brake and the tactics they use during braking. Nevertheless, the potential promise of driver assistance as offered by ACC systems makes them a good candidate for serving the nation's interest in highway safety.

2.0 Introduction

The overall goal of the FOCAS program is to facilitate the development of a range of commercialize-able sensors and associated applications systems that complement and supplement the forward crash-avoidance performance of drivers. To aid in progressing towards this goal, the program has created evaluation tools, methodologies, and knowledge-bases as needed to expedite the development of adaptive cruise control (ACC) systems as well as systems providing forward collision warning (FCW) alerts.

The expertise and equipment provided by UMTRI's partners at Automotive Distance Control Systems GmbH (A.D.C.) and Conti-Teves made this program viable. They provided sensors, communication and computation subsystems, and actuators. UMTRI personnel integrated these components and created ACC and FCW algorithms as needed to develop working ACC and FCW systems. Using the sensory equipment provided, and data gathering and data processing systems developed by UMTRI, we studied manual as well as ACC control of the driving process. We gathered data pertaining to the performance of lay persons driving on public roads. In addition, the techniques developed in this program and a related field operational test of ACC [1] have contributed to the development of a knowledge-base concerning both manual and ACC driving. The resulting data and knowledge-base have been used to study proposed FCW algorithms.

Section 3 describes the work performed during the first three years of the FOCAS program. Annual reports have been published covering these activities in detail [2], [3],and [4].The efforts in these years are concisely summarized in section 3.

Sections 4 and 5 pertaining to years 4 and 5 respectively, provide material describing our latest work on ACC-with-braking and forward-collision warning (FCW). These sections describe work that has not been reported previously. Consequently they contain the level of detail typically found in stand-alone annual reports.

The material presented for each year is organized into subsections covering the following areas:

1. System Configurations
2. Research Activities
3. Analysis Methodology
4. Results
5. Findings, Conclusions, and Recommendations

The material presented in Section 5 (on year 5) also describes research directed at the study of FCW algorithms.

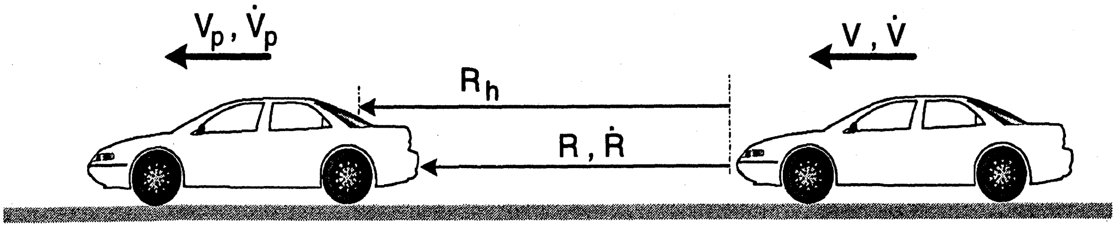
The report concludes in section 6 with a synopsis of the contributions of the FOCAS program to knowledge concerning driver assistance systems.

2.1 Research Questions

In order to explain the driving situations that we have been studying, it is convenient to introduce terminology that applies to the speed of the ACC-equipped subject vehicle, and to the range gap between the subject vehicle and the principle preceding vehicle.

As illustrated in Figure 1, the following fundamental quantities are useful in describing situations in which the driver of the subject vehicle is trying to control speed and range:

V_p — velocity of the preceding vehicle
V — velocity of the ACC-equipped vehicle
R — range, the distance from the ACC-equipped vehicle to the preceding vehicle
R_h — desired range from the ACC-equipped vehicle to the preceding vehicle (in the situation shown in Figure 1, the ACC-equipped vehicle is closer to the preceding vehicle than the desired range.)
$\dot{R}$ — range rate, the relative velocity between the vehicles (range rate is also denoted by dR/dt and Rdot in this report.)



Preceding Vehicle *ACC-Equipped Vehicle*

Figure 1. Speed and range control

Knowledge of these quantities plus the accelerations of these vehicles provides the basis for a kinematic analysis of the relative motion between the following and the preceding vehicles.

The acceleration/deceleration of the ACC-equipped vehicle is symbolized by dV/dt, $\dot{V}$, or Vdot. Similarly, the acceleration/deceleration of the preceding vehicle is symbolized by dV_p/dt, $\dot{V}_p$, or Vpdot.

Depending upon the context, road-fixed coordinates may be easier to use than relative coordinates such as R and Rdot. The following relationships have proven to be useful in transforming between coordinate types:

$R = x_p - x$

where x_p is the location of the preceding vehicle along the road, and x is the location of the ACC-equipped vehicle.

$\dot{R} = V_p - V$, where $V_p = dx_p/dt$ and $V = dx/dt$

And finally, with regard to acceleration/deceleration:

$\ddot{R} = \dot{V}_p - \dot{V}$

These relationships are illustrated in Figure 2 showing time histories representative of a rear-end crash event.

The ACC-equipped vehicle has special sensors. These sensors measure R, Rdot, and V. We have used this sensor information to perform engineering research addressing the following questions:

1. What is happening in situations involving control of velocity and range gap?
2. How is this control achieved?
3. What can be done with this knowledge?

In the context of these questions, we have measured driving with adaptive cruise control and manual driving without adaptive cruise control (but with the sensor still operating to collect data). The remainder of this report presents what we have discovered about the driving process and recommendations concerning driver assistance systems.

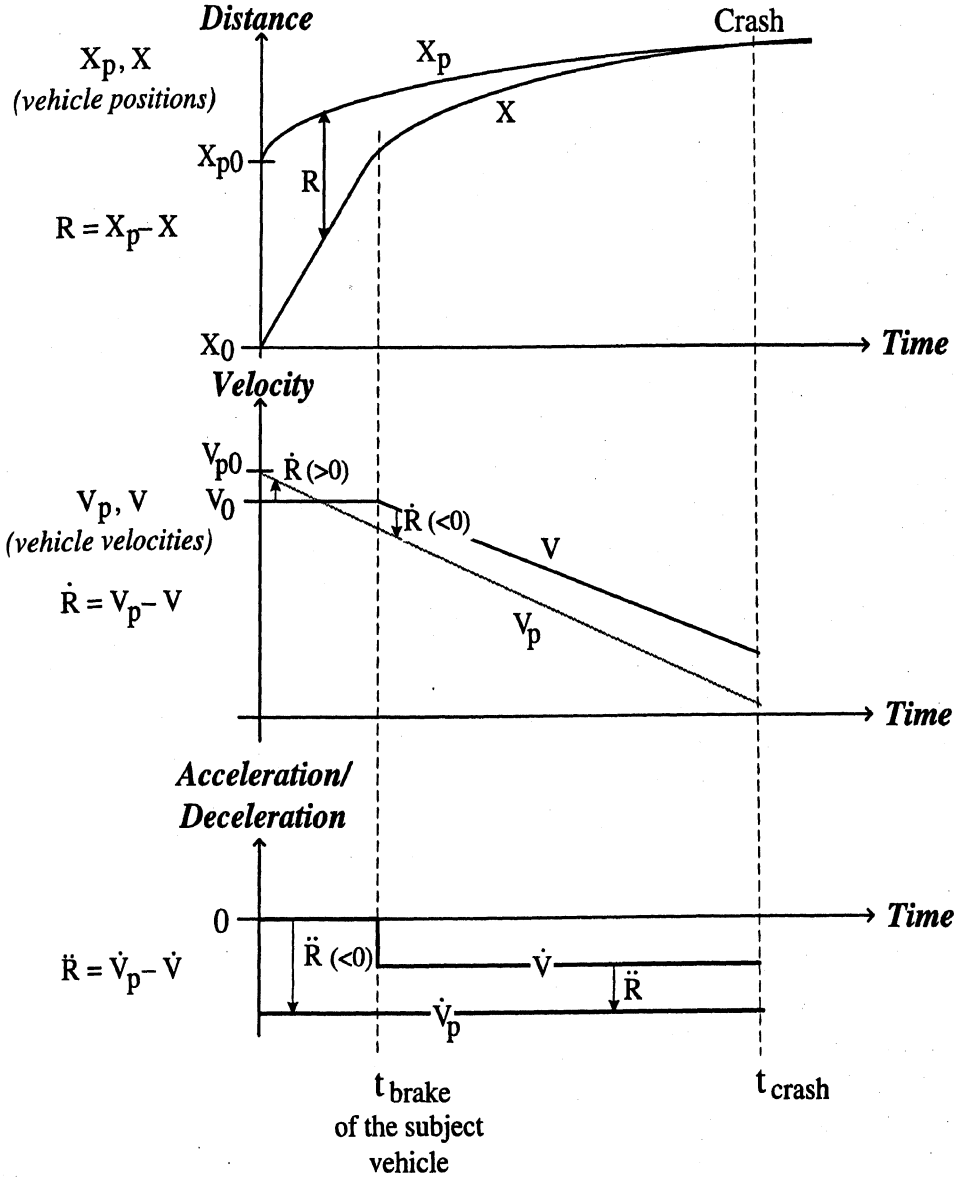


Figure 2. Rear-end crash sequence

3.0 Summaries of Years 1 Through 3

Section 3 provides overview of work performed during the first three years of the FOCAS program. Annual reports were written at the end of each these years [2], [3], [4]. Details of the research and development work performed in the first three years can be found in those reports.

This section presents capsule summaries of pertinent items that have been selected from the Executive Summary for years 1, 2, and 3. Each year is summarized by discussions concerning the cross-cutting topics of:

- ACC system configuration,
- research activities,
- analysis methodology,
- results, and
- conclusions and recommendations.

In general, quantitative information is presented in the results sections (3.1.4, 3.2.4, and 3.3.4). The conclusions and recommendations presented for each year are directed toward system concepts, pertaining to the development and evolution of ACC systems.

3.1 Year 1

This section presents the activities during year 1 of the FOCAS program. The table below provides a complete horizontal review of the activities during year 1 of the FOCAS program.

ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	RECOMMEN-DATIONS
• SAAB-based ACC system • Baseline ACC with 0.05 g decel from zero throttle coast down • Single fixed beam IR sensor • Fixed 1.4 second headway • Kinesthetic warning cue from automatic system decel.	• Freeway road testing using 36 subjects accompanied on three 55-mile drives • Driving comparisons for 3 modes - manual, conventional cruise control and ACC based driving	• Assembled objective database of driving behavior in all modes • Assembled subjective database of driver responses to comfort and safety questions; ACC acceptance and comfort questions • Conducted focus group meetings to get additional driver feelings • Developed range-range rate diagram and histogram plot methodology	• ACC system performed well; drivers followed at safer distances, with reduced closing rates • Driver aggressiveness not defined by age, gender, or cruise control experience • Driving task difficulty varies significantly with driving mode • ACC driving mode is most orderly • Available reaction time is a significant performance measure	• Revise ACC design to permit driver selectable headway; study selection method options • Add braking link to system to raise decel level to 0.1 g range • Improve performance of system on curves • Define analysis, simulation and test track methods for evaluating pre-deployment ACC • Let drivers use ACC unaccompanied

3.1.1 ACC System Configuration

The baseline ACC system used during the first year of the FOCAS study is depicted in the block diagram of Figure 3. The system was installed in a 1993 Saab Model 9000.

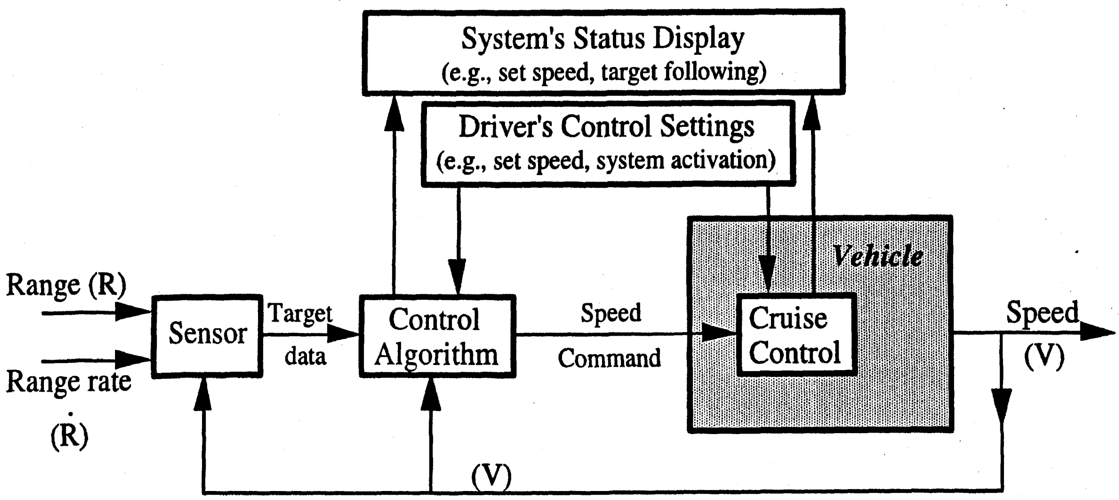


Figure 3. ACC system block diagram

Sensor

An infrared headway sensor – a Leica ODIN unit – was used to measure the distance (range) and relative velocity (range rate) between the ACC equipped car and the vehicle in front. The sensor was mounted above the rear-view mirror and behind the windshield. The sensor is a fixed monobeam type, with a field of view of ±1.5 degrees relative to the center of the car. Only one target (the closest one) is reported at any time. Momentary targets – less than 300 milliseconds – are not reported as tracked. The sensor emits a light pulse, and then measures the time until the echo of this pulse is scattered back from the target.

The sensor is capable of measuring distances from 2 to 160 meters and relative speeds between ±250 kph. The range and range-rate data are provided to the controller at a frequency of 100 Hz (every 10 msec) for targets up to 120 meters and at 10 Hz (every 100 msec) for targets further away than 120 meters.

Controller

Target acquisition is fully automatic. When the sensor detects a valid target, the controller calculates the headway distance and corresponding speed, and then sends a speed command to the cruise control. The commanded speed can be either the driver's set speed or a headway speed computed by the controller. The baseline system has a fixed headway setting of 1.4 seconds. The longitudinal control authority of the system is limited to throttle manipulation. Since brakes are not applied automatically to control speed, deceleration is limited to the zero throttle coastdown level of 0.05 g's. However, this amount of commanded deceleration is sufficient to provide the driver with a kinesthetic warning cue, calling the driver's attention to the forward scene so as to appraise whether the ACC control authority is insufficient.

The controller discriminates between targets that should be ignored and valid targets. Stationery targets, such as road signs, or traffic moving in the opposite direction, are classified as invalid targets.

Driver Controls and Display

Setting and controlling the ACC system is done using the original stalk-mounted cruise control switches. Once the system is engaged, the desired cruising speed is set like a conventional cruise control – by pushing a "SET" button when the vehicle is traveling at the desired speed. Re-engaging the system (if disconnected by touching the brake pedal) is done by pushing the "RES" (resume) side of the switch. The "SET" and "RES" buttons are also used to incrementally increase or decrease the value of the set cruising speed.

A driver's display unit includes three indicators: (1) The desired "SET" speed; (2) a green LED which shows when the system is engaged; and (3) a red LED which illuminates when a target which is valid to follow is detected.

3.1.2 Research Activities

First year research activities included instrumenting the ACC vehicle, selecting test participants, having participants drive a prescribed route, developing objective and subjective databases, and analyzing the results.

Vehicle Instrumentation

The ACC equipped vehicle was equipped with a number of ancillary transducers to record longitudinal acceleration, yaw rate, steering wheel angle and atmospheric pressure using analog sensors and an eight-bit digitizer. The resulting data were transmitted via RS-232 communications from the digitizer to a laptop computer for storage. A color video camera, two microphones and a computer-controlled videotape recorder were also installed. The tape deck recorded the forward scene and in-vehicle sounds of the driving experience whenever the laptop was collecting data from the transducers and headway sensor.

Range and range-rate data, along with several control parameters, obtained from the headway sensor and controller, were transmitted to the laptop computer at 10 Hz. The control parameters included data such as set-speeds, current speed, intervention mode, etc. The entire instrumentation package functioned independently of the ACC control system.

Test Participant's Selection

Thirty-six licensed drivers were recruited to participate in the study through a local Secretary of State's office, as well as through newspaper advertisements. Participants were required to meet the following criteria: possess a valid driver's license; have a minimum of two years driving experience; and not be under the influence of any substances that could impair their ability to drive. The participant population was balanced for gender, age, and experience in the use of conventional cruise control. The three age groups examined were 20 to 30; 40 to 50; and 60 to 70 years of age. Experience with conventional cruise was divided into groups – those who frequently used cruise and those who never or rarely used it.

Participants were briefed as to the nature of the study, its benefits and risks, and provided informed consent. They were then given familiarization instructions regarding the vehicle, controls and displays, and operation of the two cruise-control devices. Participants were accompanied on their test drives by an UMTRI researcher. They were instructed to drive as they normally would for the existing road and traffic conditions. They were asked to employ a specific type of control mode – manual, conventional cruise control, or ACC for each of three trials.

Test Drives

Each participant drove a predetermined route, covering 55 local freeway miles, and taking approximately 50 to 60 minutes. This time was believed sufficient to allow them to experience, and become accustomed to, controlling the vehicle. Each trial used a different control mode. Trial participants returned to the UMTRI research facility at the end of each experimental trial to complete a questionnaire.

Objective Data Collection

An objective database of histograms of each variable for all subjects was developed. These histograms provide immediate access to a distribution of the data and simple descriptors such as mean, mode, variance, etc.

Subjective Data Collection

Participant subjective data was collected from a comfort and safety questionnaire following each trial; from an ACC acceptance and comfort questionnaire following all three trials; and from questions asked at three separate focus group meetings. The first questionnaire asked six questions regarding participant's sense of comfort and safety across the three control modes and used a seven point adjectival rating scale. The second questionnaire asked ten questions regarding the use of the ACC driving mode only. The focus groups were asked to discuss sixteen more broadly based questions.

3.1.3 Analysis Methodology

Objective Database

Data from the field consisted of a time sequence of samples from a variety of sources, each with its own independent timing system and phase relationship to the overall system. Data synchronization within one sample period was verified and maintained. The approach used was to validate the data being transmitted to the laptop computer to ensure that the phase relationship existed and remained constant over the course of a test. A 10 Hz transmission rate was chosen since the controller installed in the vehicle had a preprogrammed output rate of 10 Hz.

Histograms of the raw data for each variable for all subjects were generated. These histograms also lend themselves to easy merging, allowing convenient comparative analyses for different subject groups and/or driving modes. Histograms for all 36 subjects were developed, including tables of means, standard deviations, variances, modes, and number of samples for each subject.

Subjective Database

Comfort and Safety Questionnaires

Following the completion of each traverse of the predetermined route, once for each of the three control modes, a brief questionnaire was completed by each of the participants. These questions were used to compare the participants' sense of comfort and safety across the control modes. The questions were worded identically, with exception that reference was made to the control mode most recently experienced by the participant. A seven point adjectival rating scale followed each question. An example question and result is given below.

- How comfortable, from a safety standpoint, did you feel while driving the car with no cruise control/conventional cruise control/adaptive cruise control? (not comfortable=1; very comfortable=7)

Control mode	mean	Std. Dev.
No cruise	6.17	1.28
Conven. Cruise	5.75	1.05
ACC	6.00	1.22

Other questions dealt with:

- Ease of maintaining safe headway
- Ability to pass other cars
- Change in speed habits
- Frequency of use of brakes
- Similarity to normal driving

ACC Acceptance and comfort questionnaire

Following the completion of all three trials, each participant was asked to complete a detailed questionnaire regarding the use of the ACC mode only. The same seven point rating scale was used. Questions dealt with:

- Whether an audible warning tone was desired
- Whether the increments for setting speed were okay
- What headway adjustment change they would like
- The impact of ACC on their sense of safety
- The impact of ACC on their sense of comfort
- Whether they became too comfortable
- How convenient the ACC was
- Whether the ACC system acceleration was okay
- Whether ACC operation was similar to their own driving behavior
- What aspects of ACC use might have bothered them

Focus Groups

Twenty-four of the original 36 participants returned to take part in focus groups concerning the ACC system they had experienced. Three separate meetings were held with seven to ten participants in each, conducted by the same researchers who accompanied participants while driving. In each of the three sessions, participants were asked the same 16 questions, with answers subsequently organized by age, gender and previous cruise experience categories. Questions dealt with:

- Advantages/disadvantages of conventional cruise control
- Convenience of ACC
- ACC similarity to normal driving
- Opinion of speed adjustment increments
- Comfort level with ACC headway distance
- Feeling more or less safe with ACC
- Experience using ACC on a curve
- Impact of ACC on sense of safety
- Impact on driving comfort level
- Opinion on ACC acceleration level; deceleration level
- Opinion on decisions regarding use of brake
- ACC features felt most beneficial
- Disadvantages of ACC
- Opinion on use of ACC for long trips

- Price willing to pay for ACC

Range–Range Rate Analysis Plot Methodology

The range R and range-rate dR/dt are key to identifying the driving state. In fact, a diagram displaying vehicle motions in a range-rate versus range space has been a feature of many papers on headway control authored by UMTRI researchers (references [5] through [9]). The use of diagrams with range on the vertical axis and range-rate on the horizontal axis are used throughout this work to display results and ideas concerning speed and range-gap (SRG) control.

The range-rate/range diagram is useful for explaining the concepts behind the SRG control algorithm used in the baseline ACC system. Conceptually, the control objective is to control range in accordance with the following equation:

$$T\, dR/dt + R - R_h = 0 \qquad (3.1)$$

This equation appears as a straight line in the range-rate/range diagram. See the line labeled "dynamics line for headway control" in Figure 4. The slope of that line (T in equation 3.1) serves as a control-design parameter.

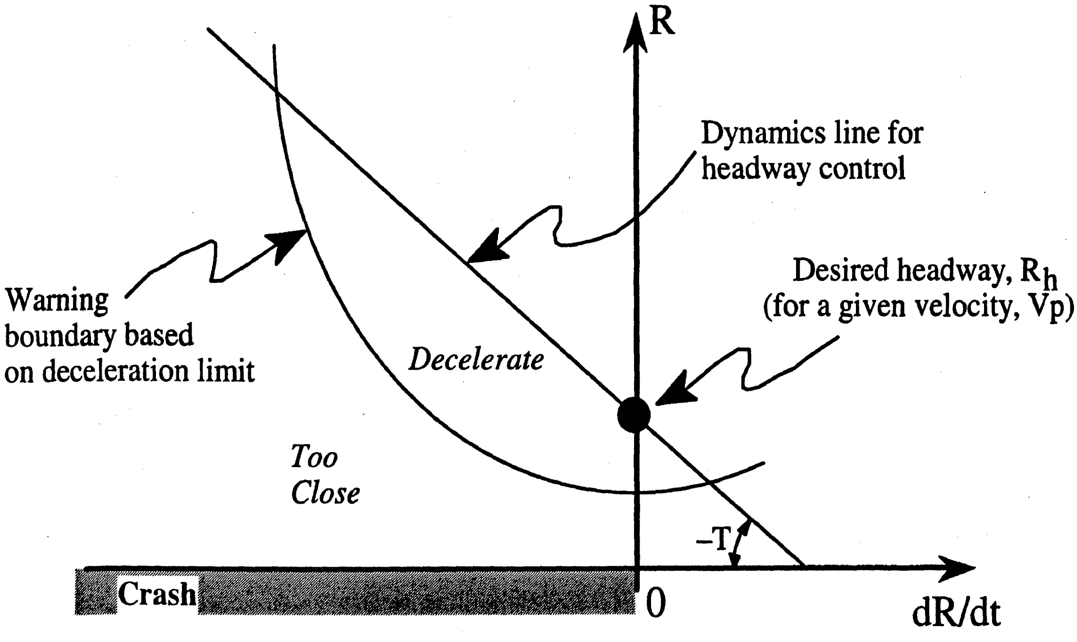


Figure 4. Range-rate versus range diagram

The desired range is a linear function of V_p, the velocity of the preceding vehicle; viz.,

$$R_h = V_p \cdot T_h \qquad (3.2)$$

where Th is the desired headway time which is a control parameter.

This equation is of the form of the commonly used advice, "Allow one car length for each ten miles per hour of speed."

Since $V_p = dR/dt + V$, measurements of V, R, and dR/dt are sufficient to evaluate the terms in equations 3.1 and 3.2. This means that the difference between the desired state and our current situation, expressed as an error e in velocity is as follows:

$$e = dR/dt + (R - R_h)/T \quad (3.3)$$

where the quantities on the right side of the equation are evaluated using inputs from the sensor and values of the control parameters.

For a vehicle with a cruise-control system, there is already an existing velocity-control system. To make a simple speed and range-gap control, one needs to send a velocity command (V_c) to the cruise-control unit, so that the desired range will be attained. The general idea is that if the preceding vehicle is too far away, one must speed up, and if the preceding vehicle is too close, one must slow down. From the above discussion, the particular velocity command (V_c) used to achieve the desired headway (R_h) is given by:

$$V_c = V_p + (R - R_h)/T \quad (3.4)$$

(If $V \approx V_c$, the error e is approximately zero, and, since Rdot = $V_c - V$, equation (1) is practically satisfied.) Equation 3.4 is the basis for a simple design method for extending (or adapting) a speed controller to include an outer control loop that achieves a range control function. The baseline ACC system is an example of an SRG control system of this type.

3.1.4 Results

1. The baseline ACC system performs well for a first generation system operating on U.S. roads.

A fixed-beam advanced cruise-control system provides drivers with an added measure of convenience through its headway control functionality. The results from this study show that drivers using the ACC do not follow as closely or with as high closing rates as they do in manual driving or with conventional cruise control (CC).

2. A database of pertinent ACC, CC, and Manual driving operations now exists.

The database contains time histories of driving for a balanced set of 36 typical drivers. The data contain information on the driving situation (range-range-rate, velocity, yaw rate and longitudinal acceleration), the driver's control actions (accelerator pedal position, brake lights on or not, and steering wheel angle), and the control system and derived variables (commanded speed, available reaction time, set speed, time to impact, etc.).

3. Data from test drives are needed to classify drivers.

The data show how drivers differ and that driver tendencies to be aggressive or passive do not follow patterns based upon gender, age or driving experience with cruise control. The characteristics of each experienced driver need to be examined in driving tests to determine their driving tendencies.

4. ACC, CC and manual are quite different modes of driving control.

With manual control the driver is modulating the accelerator pedal continuously. In conventional cruise control, the driver supervises the situation and decides when to apply the brakes depending upon a judgment of whether the headway is acceptable. Driving in ACC is characterized by the system slowing autonomously to provide headway. The driver feels even modest decelerations and is aware of when the system decides to slow at or near its level of control.

5. ACC provides more orderly control of range and range-rate while operating at somewhat longer values of range.

In manual driving, there are many more instances of shorter headway times than those encountered with ACC driving. Also, there are many instances where people do not close up the gap in manual driving. With conventional cruise control, drivers not only come closer to the preceding vehicle but they often close at a substantial level of range-rate. ACC driving occurs with a greater safety margin than driving in the manual or conventional cruise control modes of speed and headway control.

6. Available reaction time has interpretations that make for an attractive performance measure.

The field data show that headway values attained under manual and conventional cruise control yield available reaction times that are well below the ability of typical drivers to react quickly. In these cases, collisions are prevented because drivers do not slow down rapidly when there is a vehicle close behind them. Nevertheless available reaction time is a performance measure that indicates the safety margin available for use in preventing collisions.

3.1.5 First Year's Conclusions and Recommendations

1. Study methods for selecting headway times.

Headway time is a matter of concern to drivers as well as safety advocates. When traffic is fairly open and cut-ins and merges are not a frequent event, a 1.4 second headway time may be acceptable to many people, even though others may find it tolerable but too long for their styles of driving. However, in dense, high-speed traffic many people would like shorter headway times. In extremely dense traffic, experienced drivers of ACC system say that they would like 1.0 or even 0.8 seconds for minimum headway time. Several approaches need to be considered for allowing drivers to try different headways. Research needs to be done to provide a rationale for the minimum headway to be used.

2. Study warnings and modest braking.

A prototype model that incorporates braking should be developed and studied. During the first year it was evident that under certain circumstances, the coastdown deceleration capability of the test vehicle limits the performance of the ACC system. Added deceleration is needed to ensure that the performance boundaries of the prototype will better meet the driver's expectations, and will also be an advancement towards becoming a crash avoidance system.

3. Study systems with swept or multiple beams for curved roads.

A headway control system that employs a sensor with directional information should be studied. Lack of information of projecting the path of the host vehicle relative to the lateral position of the targets impedes system performance on curved roads. The mono-beam sensor can pick up false targets on adjacent lanes, or miss valid targets around the curve ahead.

4. Examine possibilities for analytical, simulation, and proving grounds tests for prototype systems.

Although on-road testing represents deploying the system in a real environment, there is a need to have techniques for studying these systems as they develop. The FOCAS project started with a deployable system. Now that the results and findings from deploying the baseline system are being evaluated, there is a need to have analytical, simulation and proving grounds techniques for examining system performance in a controlled environment.

5. Deploy systems (such as the baseline system) allowing people to operate them unescorted and for longer periods of time.

The baseline system performed very well in the hands of experienced drivers when the drivers were accompanied by an experimenter. The next step in deployment would be to have responsible drivers operate these systems without an experimenter present. There is a need to confirm that people will use these systems much as they currently use conventional cruise control systems; to assess the viability of ACC as a consumer product; and to determine its influence on driving safety margins.

3.2 Year 2

This section presents the activities during year 2 of the FOCAS program. Provided below is a complete "horizontal" review of the activities during year 2 of the FOCAS program.

ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	RECOMMEN-DATIONS
• SAAB-based ACC system • ACC downshifting to get 0.1 g decel • Driver selectable headways added • Kinesthetic warning from transmission downshift • Audible warning from range-rate signal • Limited braking warning from low-decel signal • Volvo-based ACC with 0.18 g decel	• Test of 2 driver headway selection methods; 12 subjects over two 43-mile drives • Test of 3 different warning systems • Test of ACC system with braking • Extension of analytical bases for understanding ACC and crash warning systems	• Used objective database to classify drivers into hunters, gliders and followers • Tried neural network approach to defining different driving situations • Defined range-range rate histograms for each driver and driving class • Developed analytical basis for consideration of different warning cue types • Developed analytical basis for extension of ACC comfort and convenience to crash warning domain	• Drivers prefer the adjustable headway feature; selection varies with age, but 1 to 2 seconds is good compromise • Drivers will prefer ACC with decel authority in the 0.1 to 0.2 g range • A three-stage driver warning system – downshifting, audible warning and brake-induced cue – can be considered for crash avoidance • Of 36 drivers, 8 are classified as hunters; 18 followers; and 10 gliders	• Enhance ACC test system to include braking for higher decel level • Enhance system ability to operate on curves • Additional warning system work based on time to impact, decel margin or reaction time margin • Improve system smoothness when braking is employed • Increase system utility by reducing situations where manual intervention is necessary

3.2.1 ACC System Configuration

In the second year, emphasis was on modifying the ACC system configuration to: (1) provide a range of driver-selectable headway settings and (2) provide a sequence of driver warning cues depending on the severity of the headway conflict with the targeted vehicle. Additionally, a borrowed ACC equipped vehicle was used to obtain initial information regarding a more sophisticated system which included automatic braking.

Headway Selection

A headway adjustment range of 0.7 to 2.5 seconds was provided, without displaying the selected headway value. Drivers selected headway by pressing one of two buttons – labeled "closer" and "further", respectively. A single button press incremented the headway selection by 0.1 second.

Warning Cues

Four sequential warning cues were provided, including one continued from the first year configuration. These warning cues were:

1. Coast-down deceleration which, with the throttle closed, provided a 0.05 g warning cue (carried over from year 1).
2. Transmission downshifting, which provided 0.7 g deceleration, extended ACC system control authority. When a deceleration level greater than coast-down was required, the downshift slows the vehicle more rapidly, simultaneously providing a stronger deceleration cue to the driver.
3. When a still more aggressive response is called for, and the driver has not yet intervened, an audio warning was provided. The audio warning cue activated a buzzer to gain driver attention.
4. A final stage cue, termed a "low-decel-cue", was achieved through a brake applicator device. The applicator provided one-second duration, 0.1 g pulse of the brake pedal to further alert the driver. This pulse also caused the ACC controller to disengage, requiring the driver to resume manual control.

ACC System with Braking

A 1995 Volvo, which was equipped with a LEICA ODIN 4 sensor and electronic braking, was provided by ADC for a brief series of test drives. This system had sufficient control authority to command a 0.2 g level of braking if required. The ODIN 4 sensor also employed a yaw rate sensor to aid in tracking vehicles on curves and to avoid false alarms from vehicles in adjacent lanes.

3.2.2 Research Activities

Adjustable Headway Study

Twelve licensed drivers participated in this study, four from each of three age groups: 22-30; 41-52; and 69-74. Each age group was balanced for gender and for previous conventional cruise control experience. Participants were selected at random from those who drove in the first year's study, and each had driven the same vehicle for approximately one hour. The only new feature of the vehicle was the driver's ability to adjust headway over a range of 0.7 to 2.5 seconds versus the previous fixed headway time of 1.4 seconds.

Each participant drove a 43-mile route accompanied by a research assistant. Two different headway selection methods were tested: (1) a modified method and (2) a free adjustment method. In both cases, participants adjusted headway based on their assessment of the closing situation with a preceding vehicle, without the use of any headway numeric display. Headways were adjusted using either of two buttons – one labeled "closer" and one labeled "further". Each button depression changed headway by 0.1 seconds.

In the first selection method, participants adjusted headway downward only, starting from an initial setting of 2.5 seconds, until a comfortable following distance was reached. In the second, or free adjustment method, they were allowed to adjust headway in either direction from a starting point of 1.4 seconds.

Warning Cues Design and Development

The first year ACC system design used throttle coast-down only to decelerate the vehicle. The disruption in the smoothness of the drive, due to throttle closure, also served to alert the inattentive driver to situations challenging the control authority of the ACC system. During this second year, three additional warning cue approaches were developed and implemented: a downshift cue; an audio warning cue; and a brake activation plus audio warning cue. The different functionality of warning cues is illustrated in the range-range-rate diagram of Figure 5.

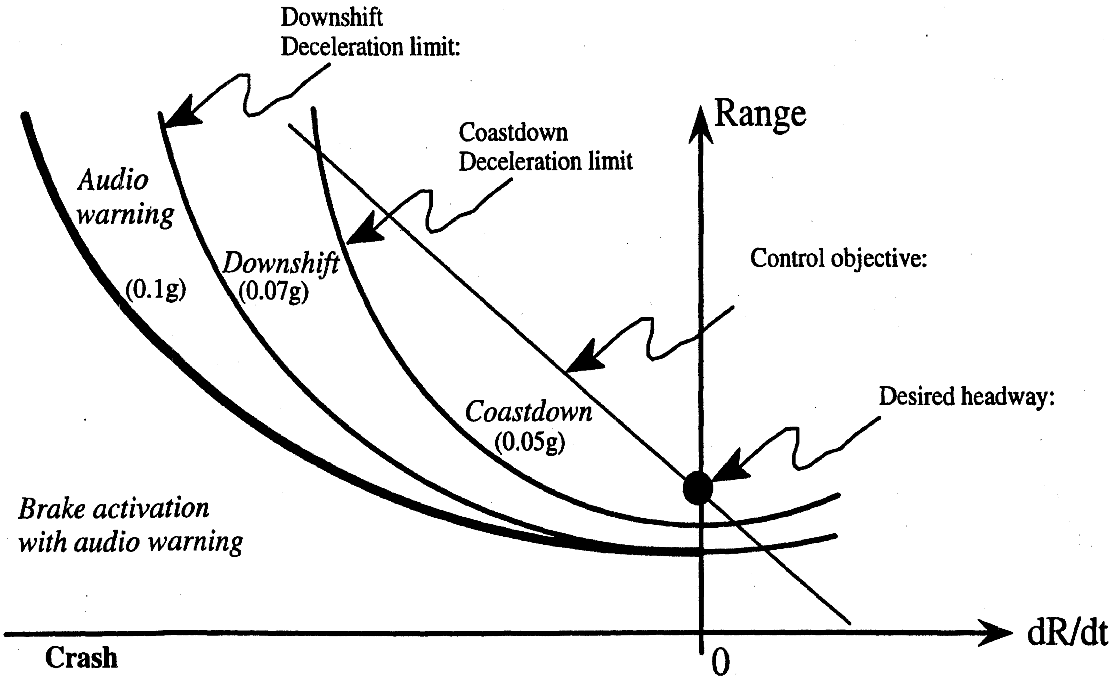


Figure 5. Warning cues functionality

The straight line represents the control objective of the headway control system. The system attempts to follow this line to converge to the desired headway. The curved lines represent different possible deceleration parabolas of the vehicle. A warning cue is issued if the system predicts that the headway gap will become shorter than some preset design parameters, which are part of the headway control algorithm.

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 is pertinent. If within the coast-down zone, the system can control the vehicle's speed using only the throttle's 0.05 g deceleration authority to reach the desired headway without getting closer than a design value to the preceding vehicle. When the vehicle is below its coast-down deceleration parabola, use of the closed throttle only will not allow the desired headway to be reached.

In the second case, when a developing headway conflict could not be resolved by means of throttle manipulation, a single-gear downshift was commanded. If the vehicle position was below this deceleration parabola, then the audio warning was issued to prompt the driver more urgently.

The final stage of warning cues was achieved through a brake applicator device. This brake applicator was devised to foster the development and evaluation of full-time crash warning systems. It employed a short (one second) deceleration pulse (0.1 g) to serve as a warning cue, at the same time initiating a significant speed reduction and disengaging the ACC control system.

Test Drive of ACC System with Braking

As a precursor to year 3 test activities, arrangements were made to borrow a 1995 Volvo equipped with a Leica ODIN 4 sensor and electronic braking. This system had sufficient control authority to apply 0.2 g if requested. The sensor in this system also used a yaw rate gyro to sweep the beam around curves, reducing target loss. The Volvo was driven in relatively heavy traffic on Detroit freeways.

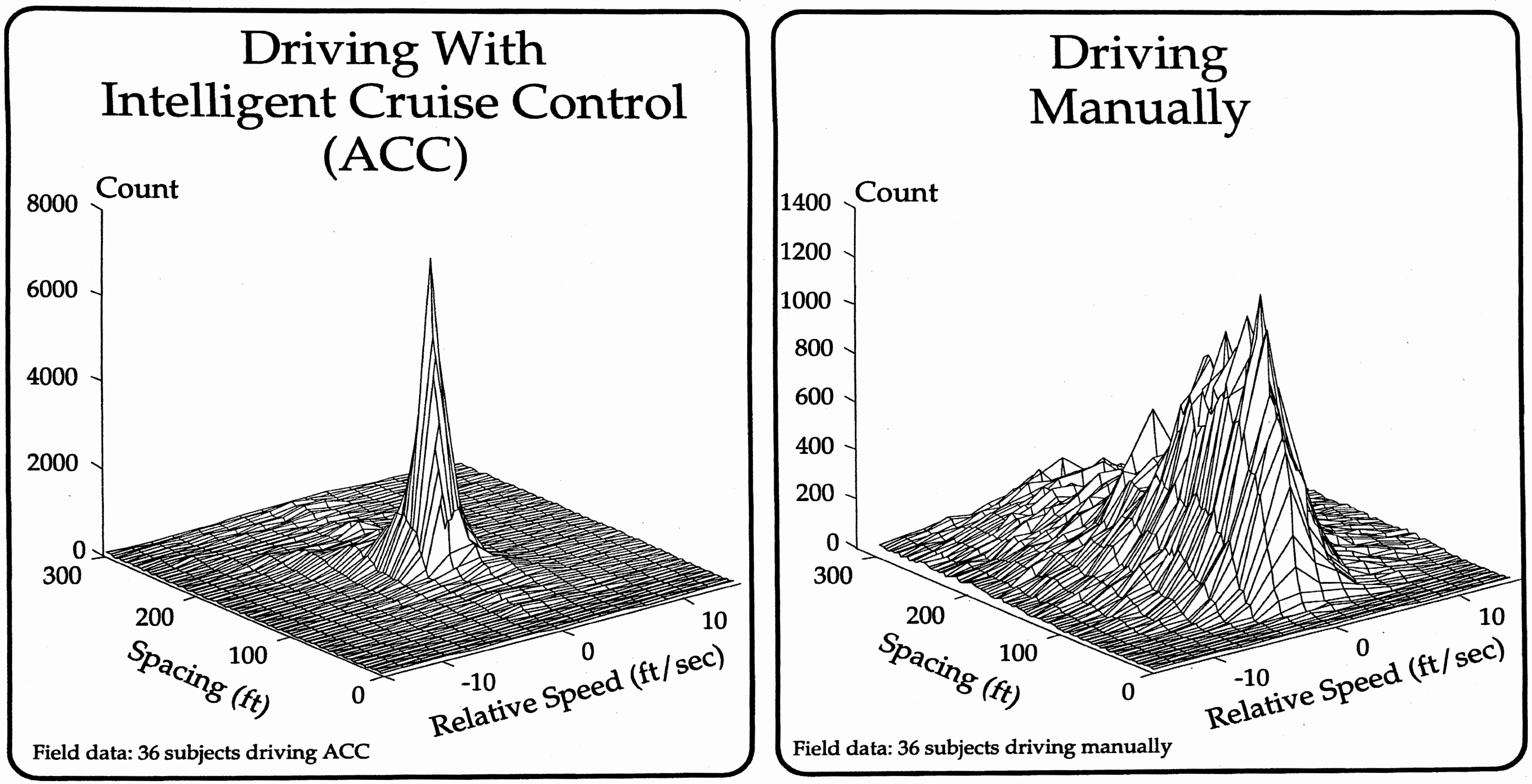
Extend Bases for Understanding of ACC and FCW Systems

Analytical work was done to provide a foundation for research on situations involving braking. The subjects covered included time to impact, deceleration demand, maximum deceleration authority, control architecture for ACC with braking, and an algorithm for controlling brake operation.

3.2.3 Analysis Methodology

Portraying Driving Performance Using Range-Range Rate Diagrams

Results obtained from year 1 data 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. During the second year, range, range-rate histograms were used to graphically analyze these differences. Parts a and b of the Figure 6 below demonstrate the orderly nature of ACC driving as compared to manual driving. Manual operation involves a considerable amount of driving at shorter ranges and relatively larger closing rates.



a **b**

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

Figure 6. Comparison of ACC and manual driving

Driver Classification by Headway Time and Average Speed

A scheme was developed by which drivers were clustered into three different groups – hunters, followers or gliders. This differentiation was based upon the most likely headway chosen and the average speed achieved relative to other traffic. Those traveling at short headways and above average speeds were termed hunters; those traveling with the traffic flow and headways similar to other cars were termed followers; those traveling at longer headway and slower average speeds were termed gliders.

Figure 7 below demonstrates this classification scheme. In this figure, average values of range-rate are plotted against the most likely value of available reaction time for each driver, according to age group. As shown, of the 36 participant drivers, 8 were classified as hunters, 18 as followers and 10 as gliders.

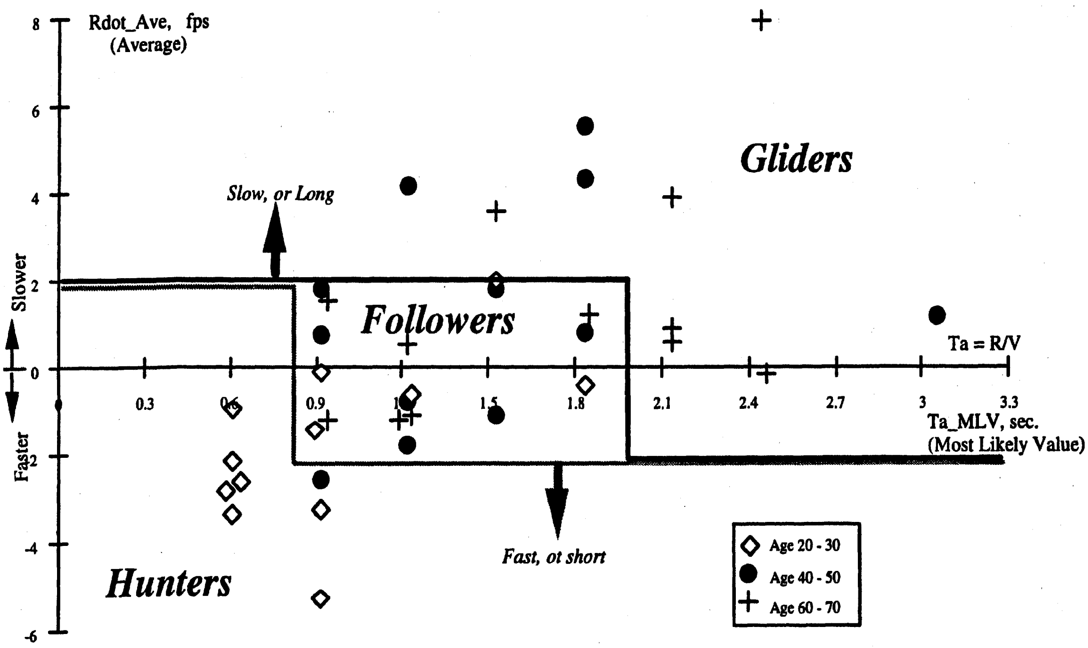


Figure 7. Drivers classification

Methods for Finding Types of Driving Episodes

A new method was explored for identifying different types of driving scenarios that are captured within the FOCAS database. This method used neural network techniques in an attempt to streamline the data interrogation process. Initial analyses used these techniques to identify and classify different types of driving scenarios, including merging; exit ramp encounter; constant speed following of a target; sudden lead vehicle slow downs; ACC vehicle closing-in; chasing a lead vehicle; cruising with no target; and manual driver interruptions.

Crash Avoidance vs. ACC

A useful construct for accident mitigation involves three dimensions: (1) eliminating risky situations; (2) reducing the probability of a crash, given the presence of a risky situation; and (3) reducing the severity of injury given the likelihood of a crash. During the second year, these possibilities were analyzed from four different viewpoints. First, operational aspects were examined, separating comfort and convenience features from safety features. Next, time-to-impact, deceleration demand, and maximum range criteria were examined as candidates for use in warning a driver. Third, the question of ACC system braking authority vs. the expected existence of sensor false alarms was discussed. Lastly, the dangers posed by stopped objects, as related to driver supervisory ability with high braking authority levels, was reviewed.

3.2.4 Results

The second year effort has added understanding and improved methods for studying higher level functionalities of ACC systems. Major issues remain in transitioning from ACC as a comfort and convenience system to systems that will provide a certain level of crash warning and/or crash avoidance capability.

When controlling headway manually, drivers tend to follow preceding vehicles at a closer range and to close-in more rapidly than they do with ACC – for the case where the ACC system has a fixed minimum headway time. However, the study of adjustable headway in an ACC system indicates that, if given the capability to do so, drivers will use headways comparable to those used when driving manually. The testing done during the third year shows that (1) many drivers would select a minimum headway down to the 0.7 second minimum of this study, or even lower; (2) an adjustable headway feature is needed so that different drivers can tailor the ACC's headway time setting to the existing road and traffic conditions; (3) younger drivers tend to select shorter headways, while older drivers are not inclined to choose headways less than 1.4 seconds; and (4) a range of headway times from 1.0 to 2.0 seconds was found to represent a compromise that appears to be satisfactory to a wide range of drivers. Selection of the allowable range of headway times is a design issue for future ACC systems.

This year's work also included the development of three different warning system cues, using some combination of deceleration inputs and audio warning. The choice of parameters in the deceleration parabolas that delineate the boundaries for audio warning and downshift functions can be chosen to ensure that downshift precedes audio warning. This ensures that the driver receives a two-stage cue indicating the need for additional deceleration. A brake-induced cue was developed as a third and final stage of warning that comes after the downshift and audio warnings have occurred.

Limited experience operating an ACC system having approximately 0.18 g of controlled braking capability was also obtained. 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.

3.2.5 Second Year's Conclusions and Recommendations

Using the experience of the first two years, a list of some 32 potentially important attributes of an ACC system was defined for consideration as the program progressed to the next stage. Based on these attributes, it was recommended that third year ACC development include:

- Enhanced ability to act with more authority by including braking
- Enhanced ability to operate on curved paths, thereby limiting the number of false alarms and missed targets
- One or more warning systems to raise the situational awareness of the driver
- Enhancing the smoothness of system operation when braking is employed
- Increased utility through reduction in the number of situations where manual intervention is necessary

3.3 Year 3

This section presents the activities during year 3 of the FOCAS program. Provided below is a complete horizontal review of the activities during year 3 of the FOCAS program.

ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	RECOMMEN-DATIONS
• Chrysler Concorde-based ACC system • Sweep IR beam plus cut-in detection sensors in car grill • Brake-by-wire braking system for 0.22 g decel • Headway and braking algorithm • Eight headway settings, from 0.6 to 2.0 seconds • Warning buzzer when system commands full 0.22 g braking	• Development of a rule-based algorithm for ACC system with braking • Development of warning feature with adjustable attention-getting thresholds • Incorporation of data acquisition system from FOT program • Development of a new driver interface • Fourteen researchers tested and evaluated the new system in five prescribed driving situations	• Extended braking rules and their implementation, considering safety, driver priority, driver compatibility, comfort and lack of ambiguity • Developed debriefing questionnaire to obtain subjective test results	• A system decel level of 0.22 g's is good for a high percent of headway conflicts on the highway • Drivers are quick to intervene at 0.22 g conflicts • Warning system is controversial; features need improvement • Algorithm has shortcomings in oscillations, smoothness and brake delay • Resume accel level is unsatisfactory	• Rules for generating velocity commands to be changed to get higher accel level • Braking algorithm to be modified to function more progressively • Limit range of adjustable headway settings to 1.0 to 2.0 seconds • Revise warning system buzzer to a less aggressive sound; consider second signal • Complete test using lay drivers • Focus on countermeasures to reduce exposure to risk

3.3.1 ACC System Configuration

A new ACC system was implemented during the third year of the FOCAS study. This ACC system employed braking in a continuous manner as an integral part of headway keeping. The new system was installed in a Chrysler Concorde five-passenger sedan, based on past experience using this type of vehicle in the field operational test (FOT) program. A block diagram of the control architecture is provided in Figure 8.

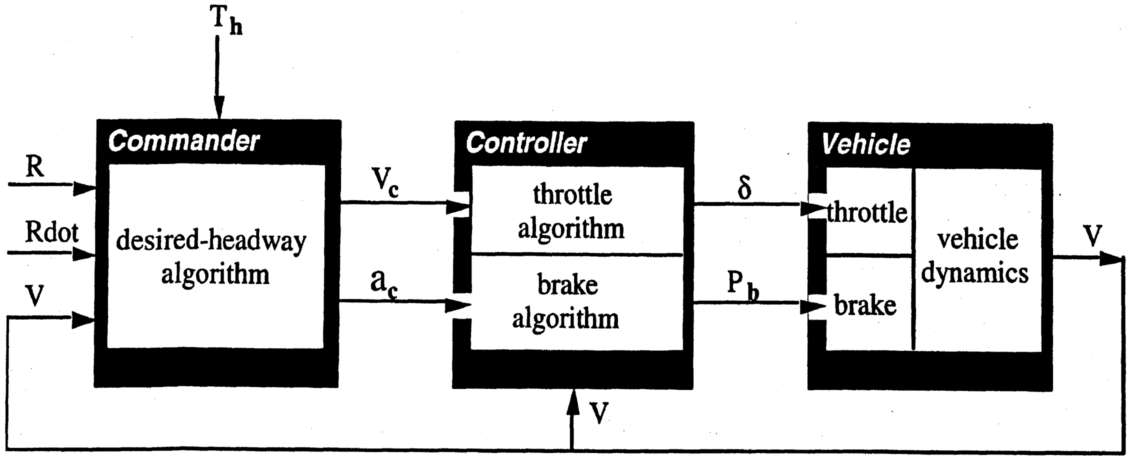


Figure 8. Control architecture for the ACC system with braking

The commander function is targeted at reaching a planned desired headway using an algorithm employing four inputs: the actual range to the preceding object in its path; the rate of change of that range; the velocity of the host vehicle; and the desired headway time.

The controller translates commander outputs into control actuation commands. The controller consists of two modules: the throttle algorithm, converting desired speed into a throttle position, and the brake algorithm, converting desired deceleration value into a brake pressure command.

Sensor

The system used two IR sensors, termed ODIN 4, as supplied by ADC. Both sensors are installed in the Concorde grill. The sensor coverage areas are shown in Figure 9. The sweep sensor is a laser-based infrared beam which is steered in response to commands from a solid state yaw gyro.

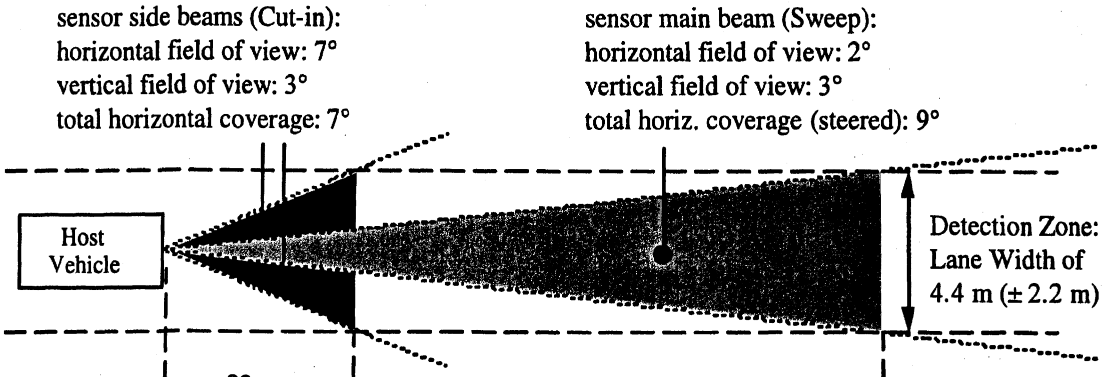


Figure 9. ODIN 4 sensors' coverage areas

This sensor detects targets in the far field (6 to 150 meters ahead). The cut-in sensor has a fixed beam and limited range. It senses vehicles that might cut-in close to the front of the test vehicle (within a range of 0 to 30 meters). Both sensors operate by transmitting pulses of infrared light energy at a wavelength of 850 nanometers and a frequency of 10,000 pulses per second. Range and range rate are determined by the time of flight of an echo pulse returned from a target vehicle.

Controller

The controller combines the functions of two algorithms – for throttle control and for brake control – as developed by UMTRI. These algorithms are designed to provide the driver with the multiple functions of safety, adjustability to accommodate different driving styles, smoothness of response, and lack of ambiguity when responding to headway conflicts. Various braking and velocity control rules were incorporated to allow experimentation with settings and identification of values that are acceptable to drivers.

Details about the control algorithm, the braking rules, and the controller's parametric design are provided in section 2.5 of the third annual report [4]. Table 1 lists parameter values that were experimented with, as well as the values selected to be used during testing. The symbols in parentheses are those used in the discussion in reference [4].

Table 1. Parameter variations of the controller

Parameter	Range of values tried (some are estimated)	Value used in testing
Minimum-control deceleration value (a_{min})	0.01	0.01 g
Coastdown deceleration (a_{coast})	0.04	0.04 g
Minimum-braking deceleration (a_{Bmin})	0.04 – 0.07	0.04 g
Maximum-braking deceleration (a_{Bmax})	0.22	0.22 g
Portion of desired headway below which braking is applied (K_2)	0.7 – 0.9	0.85
Slope of the control-objective line (K_3)	10.0 – 12.0	11.0
Portion of desired headway below which maximum braking is applied (K_5)	0.4 – 0.7	0.65
Gain factor (K_7)	0.5 – 2.0	1.0
Slope of the control-objective line during following (T_f)	0.5 – 2.0	2.0 sec.

Vehicle Actuators

The two key actuators controlled by the ACC system are the smart booster and the throttle control. The smart booster, used for brake actuation, is a direct replacement for the conventional vacuum booster in the car. This new booster is a pre-production prototype, developed over the course of several years by ITT Automotive. The smart booster receives serial digital data as a brake pressure command and delivers corresponding four-wheel brake application at the commanded level of hydraulic line pressure.

The throttle control algorithm directly controls throttle displacement within the OEM engine control unit. However, since throttle response is determined by the design of the cruise control unit existing in the Concorde, the achievable acceleration level is limited.

Driver Controls and Display

The driver interface includes a display for presenting the set speed to the driver; a light accompanied by an audible tone for indicating when the ACC sensor's performance is inhibited by visibility; and a light for indicating when the ACC system has recognized a preceding vehicle. In addition, a thumb wheel switch is provided for driver selection of headway time. This switch allows headway adjustment from 0.6 seconds to 2.0 seconds, in increments of 0.2 seconds.

Warning System

An active warning function was integrated into the system's design. The warning system activates a buzzer, based on a rule that is stated as follows: whenever a conflict is such that the ACC system is asking for its full level of brake application, the buzzer will sound. Actuation of the buzzer does not mean that a crash is imminent or even that intervention is required. Rather, the purpose of the warning buzzer is to call the driver's attention to the forward scene. The driver then needs to evaluate the situation and make a decision regarding the need for further action.

3.3.2 Research Activities

Braking System Algorithm Development

In the early FOCAS ACC systems, deceleration was set at the coast-down level (0.05 g) or, later, at the value that could be achieved by downshifting the transmission by one gear (0.07 g). Whenever range and range-rate data from the sensors fell below the coast-down deceleration parabola, added deceleration was provided by the transmission downshift, which was able to add only 0.02 g of added authority. With the availability of the ITT smart booster, the control authority of the ACC algorithm was significantly expanded, such that headway conflicts that would have saturated the throttle-plus-downshift controller, could now be managed. The new command module, which computes a desired deceleration, is now incorporated into the headway algorithm. The algorithm that controls the brakes uses the computed value of desired deceleration.

Several control strategies and algorithms were developed to incorporate automatic braking concepts. These concepts were subjected to experimental evaluation. Some involved a single braking level that was invoked when the range and range-rate coordinates dropped below the coast-down parabola (e.g., a fixed 0.15 g brake application when some threshold is crossed). This is similar to the concept for invoking downshifting, but with a higher deceleration level. Other algorithms involved a simple longitudinal model of the vehicle for in-vehicle computations. Several other algorithms approximated the basic design that was employed in the ACC Field Operational Test program. These involved gains that could be adjusted with various schemes for gradual brake application. (For example, applying 0.07 g when coast-down is just not enough. and gradually increasing the braking intensity as the situation becomes more demanding, up to the maximum of 0.22 g.) Each algorithm was programmed into the vehicle controller and a short sequence of characterization tests was performed with the test vehicle. These tests were aimed at allowing both qualitative and quantitative evaluation of such ACC system designs.

An additional adjustable parameter, that was used during the system development stage and the initial testing, was a jerk rate limit. This limit simply governs the rate at which brake pressure commands are changed, thus avoiding the uncomfortable jerk response that the smart booster is capable of achieving. Incorporation of adjustable parameters into the various braking and velocity control rules employed in the new ACC test vehicle allowed experimentation with settings and identification of values that were acceptable to drivers.

Instrumentation Package Development

A new data acquisition system, based on the system used in the FOT program was developed and installed in the test vehicle. The key part of this system is the on-board computer, which not only controls the gathering of data but also conducts on-line data processing. The data computer system collects and records data from the headway control system, the vehicle itself (via the headway-control system) and a GPS system. The data are organized by trip, whose duration extends from ignition on to ignition off. The data computer also performs on-line data processing to generate derived channels, histograms and summary counts. The processed variables are acquired from the Leica sensor, the control algorithm, the automotive electronics bus, the man-machine interface and the GPS.

Driving Tests

The new ACC vehicle was driven and evaluated by 14 researchers whose familiarity with ACC systems ranged from very basic to very experienced. A prescribed set of five driving situations was established to ensure that (1) each test driver was exposed to a similar set of operating conditions; and (2) the scope of the system's performance range would be explored in an efficient way. Each of the participating drivers was given a list of the driving situations and was asked to drive at least long enough to experience these situations and to be able to answer questions regarding them.

Since testing was accomplished on public roads, it was feasible to cover a broad set of operating scenarios in a relatively short driving trip. Each of the five prescribed driving situations was selected to elicit a certain response that would serve as a meaningful exercise of the system. During these tests, data were collected using the instrumentation package described previously.

The approach employed for determining the driving situations was based upon identifying generic, fundamental tasks that the system was expected to perform. The drivers were requested to exercise the ACC system and then answer questions regarding the following situations (more details about the procedures involved with each driving situation are provided in the third annual report [4]):

1. Closing in on the preceding vehicle – examining the ACC transition from the speed control mode to the headway-control mode.
2. Following a vehicle – seeing how well the ACC system maintains headway during nominally steady state following situations.
3. Passing – where the ACC vehicle pulls out from a following situation and automatically accelerates back to its set speed.
4. Cut-in – where a preceding vehicle appears suddenly, and at short range, in front of the ACC car, thereby exercising the system's responsiveness to a new, conflicting target.
5. Buzzer activation – obtaining observations from drivers regarding any situational cases where the ACC warning buzzer was activated.

3.3.3 Analysis Methodology

Subjective Questionnaires

Each of the participating drivers was given a debriefing sheet that included specific questions regarding the five driving situations. Appropriate space was provided for free-form comments or observations regarding the system's overall functionality. Driver judgments were sought on situation questions including the following:

1. Closing in on a preceding vehicle
    - The range at which the system initiated its response
    - The appropriateness of the system deceleration rate
    - Driver awareness of the system's actions
    - Smoothness of closing-in
2. Following a vehicle
    - The selection range of headway settings
    - The smoothness of the system while following
    - The system's ability to maintain a selected headway
    - The appropriateness of the transition to a longer headway
    - The appropriateness of the transition to a shorter headway
3. Passing
    - The smoothness of acceleration
    - The appropriateness of the acceleration rate
4. Cut-in
    - Timeliness of the system's response
    - Appropriateness of the deceleration rate
    - Driver's awareness of the system's actions
5. Buzzer activation
    - Timeliness of the buzzer
    - Contribution of the buzzer to safety
6. Free-form comments
    - System's general performance
    - Sensor operation
    - Algorithm design
    - Perceived oscillations and smoothness

- Acceleration comments
- Brake application comments
- Buzzer operation

3.3.4 Results

Subjective responses were provided by the drivers through questionnaires (see section 3.3.3 above) in two forms: (1) scaled rating, and (2) narrative description of their driving experience and issues they wanted to comment about. Detailed summaries and histograms of the responses are presented in section 3.2 of the third annual report [4]. The following bulleted lists highlight the important feedback on performance of the system implemented in the third year.

Design Issues

- Deceleration authority – The maximum deceleration authority of 0.22 was adequate
- Jerk level – The chosen level of 0.6g/sec was satisfactory most of the time, but might be too steep in certain situations
- Warning – Various levels and thresholds need to be explored further
- Display – Assumed to be adequate, although not specifically addressed in questioning
- Headway time range – Probably needs to be limited to a 1.0 to 2.0 range because of the current acceleration limits
- Acceleration – Criticized by nearly every driver as inadequate
- Speed boundaries – The minimum values of 30 mph to set and 25 mph to resume seem appropriate; same for maximum set value of 85 mph
- False deceleration – The system has proven to be very unsusceptible to unexplained false decelerations
- Vigilance and inattentiveness – The system deceleration level of 0.22 g takes care of a high percentage of system conflicts and even when 0.22 g conflicts occur, drivers are instinctively quick to respond.

Subjective Results

- The acceleration level used in increasing the speed of the ACC vehicle was unsatisfactory.
- The resume rate of the system was the system's weakness. Drivers did not want to slow down too much because of concern over getting back up to desired speed.

- The ratings of the buzzer warning system were controversial, ranging from excellent to marginal.
- The ratings of the deceleration level, following control and system smoothness were all quite good, with 87 good ratings, 29 excellent and only 12 marginal or bad.
- Oscillation and smoothness comments indicated that drivers felt the algorithm for following permitted too much oscillation.
- A number of comments regarding brake application indicated that brake application was delayed relative to driver preferences.

3.3.5 Third Year Conclusions and Recommendations

The experience that was accumulated during the third year yielded several important observations and recommendations for development work in the following years. These are provided in details in section 4.2 of the third annual report [4], and are summarized in a concise form below.

1. A simple rule for modulating the throttle should be used to achieve basic ACC functionality to improve smoothness.
2. The braking algorithm should be improved in a manner to lead to headway time and distance gaps such that throttle modulation can control headway with braking applied in a progressively increasing manner (quantitative results pertaining to this recommendation were determined in year 5).
3. Effort should be made to improve the forward acceleration of the vehicle when under ACC control.
4. The headway adjustment range should be limited to 1.0 to 2.0 seconds.
5. The warning system should have a non-aggressive signal (such as a more friendly "beep-beep") to inform drivers when braking at the full deceleration of the ACC system has been reached. Further consideration should be given to adding a second, more aggressive, signal when deceleration needed to barely avoid a crash exceeds the control authority of the system.

4.0 Year Four Report

This section presents the activities during year 4 of the FOCAS program. Provided below is a complete horizontal review of the activities during year 4 of the FOCAS program.

ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	RECOMMEN-DATIONS
◆ Basic system features are those developed in year 3 ◆ Graduated braking applied when throttle modulation is not sufficient for controlling range and range-rate ◆ ACC with various braking algorithms ◆ Preceding vehicle deceleration considerations added to the braking algorithm	◆ Development of graduated braking rules ("UMTRI algorithm") for maintaining ACC functionality ◆ Proving grounds tests of ACC with braking ◆ Study of driver intervention characteristics for use in designing ACC with braking	◆ Examined test results for manual and ACC driving to study (1) driver headway time in manual driving, (2) when drivers choose to brake when closing, and (3) how much braking the driver decides to use ◆ Studied looming coefficient and braking target point ◆ Developed "personalized algorithm", an adjustable controller to fit each driver's characteristics ◆ Applied subjective ratings and evaluation of the ACC-with-braking system including preceding vehicle deceleration ◆ Developed a computer model for simulating ACC performance. (Not exercised extensively in the 4th year)	◆ Invented interpolation rules for selecting level of braking ◆ Created test procedures for use in proving ground situations ◆ Subjective ratings indicate that lay driver felt comfortable with the ACC-with-braking system	◆ Proving-grounds tests recommended for checking out vehicle and control system properties ◆ Proving-grounds tests not generally recommended for determining driver interaction with ACC ◆ Valid testing of ACC driving should be done on a freeway A deceleration algorithm augmented to consider preceding vehicle braking was found to be satisfactory and it was recommended that the amount and timing of the response to braking be tuned to meet driver preferences

4.1 Introduction to Year 4

Based upon the knowledge gained during the third year, the objectives for the fourth year were to

1. assess system-level issues associated with a "basic" ACC-with-braking function,

2. identify testing methods suitable for human use of an ACC-with-braking function on a proving grounds facility, and
3. make an initial assessment of prospects for operating on freeways using lay drivers employing the ACC-with-braking system.

The plans and expectations for the fourth year involved testing on a proving ground. The primary reason for going to a proving ground was to try the ACC with braking system in controlled situations. This provided the opportunity to assess driver performance with the system before taking the next step of operating the system on the highway. In highway driving with ACC, the driver needs to be able to supervise the system. The level and timing of braking can have an important influence on the driver's ability to judge the safety qualities of the driving situation.

In addition, the tests were aimed at trying to ascertain certain characteristics of the drivers themselves. Specifically, attempts were made to estimate the driver's preferences concerning (1) time gap and clearance range to a preceding vehicle, (2) the point where the driver becomes anxious in either closing or lead-vehicle-braking situations, and (3) the levels of deceleration that drivers use when they become anxious.

The following subsections describe the work performed and the results and findings obtained. The material is organized according to the structure of the summary chart entitled FOCAS Year 4 presented in section 3. The subsections respectively address the variations in the ACC systems used, the research activities performed, the analysis methods used, the results obtained, and the findings, conclusions, and recommendations reached.

4.2 ACC System Configuration

The test-vehicle platform and the elements of the ACC system hardware that were deployed during the 4th year were largely unchanged from the previous year. The hardware configuration consisted of the following:

- Chrysler Concorde, model year 1996
- Infrared range sensors with the associated electronics by ADC
- Electronically-controlled brake actuator ("Smart Booster") by Continental-Teves (formerly "ITT-Automotive")
- Data acquisition system (DAS) mounted in the trunk

ACC With Braking

This ACC-with-braking system has been refined in accordance with the recommendations presented in the third annual report [4]. Most of the time, speed and headway were controlled by throttle modulations. In this modus-operandi the ACC-equipped vehicle operated much like one of the Chrysler Concords used in the ICC FOT [1]. However, when a more drastic headway conflict was presented to the system, its control authority for deceleration has been increased by using the foundation brakes. When throttle modulation is not sufficient to control range and range rate within prescribed bounds, the foundation brakes are used to apply deceleration in a graduated fashion running from approximately 0.07 g up to 0.22 g (maximum). This means that the headway control algorithm has been expanded to provide pressure commands to the smart booster provided by Continental-Teves.

In contrast to the ICC FOT, downshift is not commanded to the transmission. The brake-pressure commands are determined by rules that have been incorporated into the headway-control algorithm, and which depended upon the existing measurements of range and range rate. Nevertheless, even with the ACC-with-brakes system in action, the driver is expected to intervene with manual braking when the driving situation warrants it.

Algorithm Variations

Since the research activities during the fourth year were aimed at investigating issues associated with the ACC-with-braking functionality from both the system design and the human operator perspectives, provisions were made to allow flexibility in the control algorithm. By using a laptop computer, it was possible to modify operating parameters of the algorithm on-the-fly, or to upload different designs with altogether different braking rules. An adjustable driver model that was incorporated into the control algorithm allowed for investigating the possibility of tailoring the ACC system to individual drivers.

The headway control system design accounted for eight parametric variables (see Figure 10):

1. the range at which the driver desires to follow the preceding vehicle under steady-state conditions
2. the maximum range beyond which the driver would not consider the vehicle ahead

3. coastdown deceleration of the vehicle (0.04 g in the case of the Chrysler Concorde)
4. deceleration when minimum braking is applied (0.07 g in the case of the Chrysler Concorde)
5. a predetermined maximum deceleration level for deployment by the controller (0.22 g)
6. the lowest acceptable overshoot amount of desired headway when approaching by coastdown deceleration
7. the lowest acceptable overshoot amount of desired headway when approaching by minimum braking deceleration
8. the lowest acceptable overshoot amount of desired headway when approaching by the controller's maximum braking deceleration

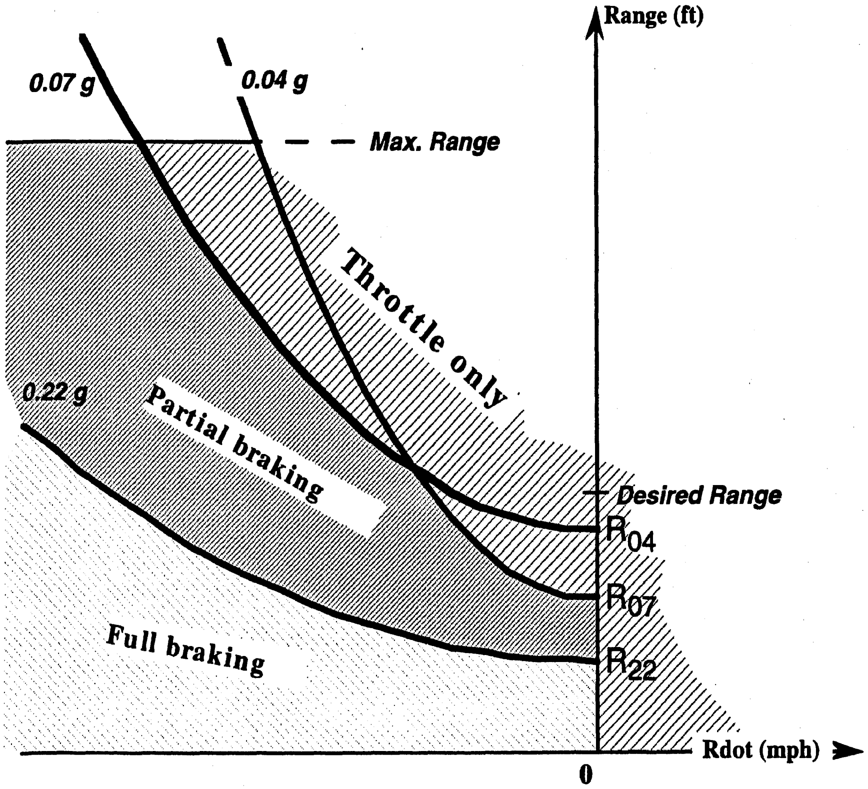


Figure 10. Parametric algorithm design

This design is mapping-based. This means that each range and range-rate (Rdot) data point provided by the sensor is mapped into Figure 10 using the appropriate coordinates, and action is then taken based on the zone within which the data point is located. If the range is more than a prescribed maximum value, no action is taken, and speed is maintained. If the range and range-rate coordinates are located in the area marked "Throttle only" (partially cross hatched), then headway control is done only by throttle modulation (no braking). If the data point is in the area marked "Full braking", maximum braking authority of the controller is applied. The area marked "partial braking" involves dropping the throttle and modulating the level of braking.

Preceding-Vehicle-Deceleration Feature

Another configuration that was employed during the third year involved active response to the deceleration of the lead vehicle. In addition to "where we are" in the range versus range-rate space, it is almost equally important for drivers to anticipate if a threat is developing. For example, closing on a vehicle whose velocity is decreasing (e.g. because the lead car is braking), is a much more stressful scenario than when the lead car is at the same range, range-rate coordinate, but pulling away. Clearly, this ACC system, being autonomous, does not communicate with other vehicles to receive information about their acceleration. Therefore differentiation algorithm was developed to perform on-line processing of the data, and to compute the rate of change of the lead vehicle's speed. The ACC control algorithm was changed so that it shifts the initiation point and modifies the intensity of brake application based upon information concerning the deceleration of the lead vehicle.

4.3 Research Activities

Introducing braking into headway control involves complex issues. Results from focus group briefings during UMTRI's operational field test of ACC, indicated that people were not receptive to the idea of automatically activating the foundation brakes by a control algorithm. It was perceived as giving up too much control. We hypothesized, however, that, if the controller were to apply the brakes in a way that is smooth, predictable, and compatible with the driver's own braking characteristics, drivers would accept ACC with braking. Research activities during the 4th year were mostly focused on studying pertinent aspects of manual braking, and applying the resultant observations in the design of an ACC-with-braking system.

Development of Gradual Braking Rules

Based on continuous highway-driving tests and evaluation (by UMTRI's researchers), the system design depicted in Figure 10 evolved through a series of iterations. Special interpolation rules were developed to establish braking levels, particularly within the area marked as "partial braking" in that figure. Various schemes for transitioning between the no-braking, partial-braking, and full-braking zones were also devised and experimented with. The outcome of these activities was a system that we felt was safe and adequate for testing with lay drivers. This system was named, and later referred to as the UMTRI algorithm.

Proving-Ground Tests

We performed proving grounds tests with lay drivers in September of 1998. The tests were performed on an oval track at the Dana Truck Test Center facility (Dana Corporation) in southeastern Michigan, just north of the Ohio-Michigan state line. The Dana test track is three lanes wide, where one circuit of the track in the middle lane is 1.75 miles in length. The circular curves at either end have a radius of 916 ft in the center lane, which is banked for a speed of approximately 60 mph. The middle lane was used for all testing, and it was generally the case that no other traffic was present when testing was performed.

In order to recruit participants for the test track evaluation, an advertisement was placed in the Toledo Blade newspaper, classified section. The add ran for five days, and read as follows:

> The Human Factors Division of The University of Michigan Transportation Research Institute is recruiting licensed drivers between the ages of 20 and 70 to participate in an experiment investigating the use of a new type of cruise control. The experiment will be conducted on a test track just north of Toledo. Time involved is 1.5 hours and compensation is $30. Call Mary Lynn Mefford at (734) 763-3583.

Persons interested in participating contacted UMTRI and were screened to ensure they met the requirements outlined in the advertisement, and to ensure they were available to be at the test track facility when testing was planned. Twelve participants, and several alternates, were ultimately recruited. Upon arrival at the test track each participant was escorted to a classroom facility on the test track grounds. Each participant was provided with an information letter that outlined the testing and listed the risks and benefits associated with participation. The information letter was followed by an informed consent form that each participant was required to read and sign. Copies of the information letter and informed consent form are provided in Appendices A and B. Ultimately only eight participants took part in the on-track testing due to unfavorable weather conditions.

The proving ground tests involved the use of both conventional cruise control and the ACC system. Two situations that are fundamental to the ACC functionality were emphasized: (1) closing from long range and (2) impeding vehicle decelerating. A specific set of tests was structured around each scenario so as to enable the researchers to deduce particular characteristics that are pertinent to manual braking (Appendix C describes the testing sequence in detail).

Incorporating Driver Characteristics in ACC Design

The objective of the first set of tests, involving conventional cruise control, was aimed at seeing when the driver chooses to intervene in closing and decelerating situations. During CC closing, the set speed of the following vehicle was larger than that of the impeding vehicle. As the test proceeded, the range between the vehicles decreased until the driver decided the vehicle had reached the proper place to intervene by braking. The results from this test provided an indication of the conditions when the driver feels braking should start and also the amount of braking the driver feels is appropriate for those conditions

The objective of the tests involving deceleration of the leading vehicle was again to see when the driver chooses to intervene. In this test, both vehicles are proceeding at the same speed at a pre-selected value of headway range. Then the preceding vehicle decelerates in a prescribed manner. As the test proceeds, the range decreases until the driver of the following vehicle decides to intervene. The level of braking used by the driver provides data used in evaluating the driver's anxiety characteristics. These data also indicate the driver's choice of deceleration level.

Drivers experienced an ACC-with-brakes system configured per the UMTRI algorithm, and immediately thereafter (under an identical set of maneuvers) with a system which was specifically configured to represent the characteristics of the individual driver (see discussion below of the personalized algorithm). Immediately after exposure to each of the two algorithms, participants completed a questionnaire regarding their level of comfort with certain aspects of the ACC system. Driver opinions combined with quantitative physical data were examined to provide knowledge for use in determining the features of an ACC system for deployment in highway testing exercises.

4.4 Analysis Methodology

Characterization of Drivers

A methodical approach was used to characterize manual driving and braking of individual drivers. The purpose was to aid in designing a driver-compatible system of ACC with braking. This approach was based on a simplification of the driving process. In this simplification, three parametric variables are used to characterize drivers: (1) headway time, (2) intervention threshold, and (3) braking level. The first parameter describes the driver's preferred distance to follow behind a preceding vehicle. Intervention threshold is the collection of headway conditions that the driver deems intolerable, and which will prompt the driver to respond by manually applying the brakes. The third parameter, braking level, is the typical deceleration rate that the driver will employ. This model is referred to as the personalized algorithm.

The Looming Effect

At the foundation of this simplified model of driving (in headway scenarios), lies the concept of *looming* which affects how and when drivers react to headway conflicts. This concept is based on how humans perceive objects in their view. In two-dimensional terms, every object that we see is associated with an occluded angle, which is the angle between the line of sight to each side of the object (see Figure 11). As we draw closer to the object, the occluded angle gets bigger. The looming effect relates to the time rate of change of the visual angle. The algebraic relationships between range (and its time rate of change), the visual angle (and its time rate of change), and the width of the observed object are given by equations 4.1 and 4.2.

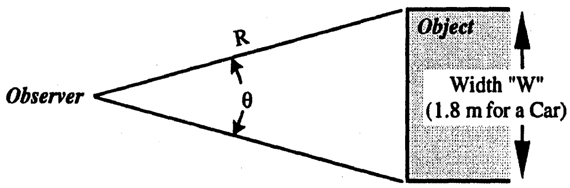


Figure 11. Visual angle θ

$$W = R\,\theta \tag{4.1}$$

$$d\theta/dt = \frac{-dR/dt}{R^2} \tag{4.2}$$

These angular coordinates are referred to as the *mind's eye coordinates.* Various researchers have studied the looming effect. One source finds that the perceptual threshold at which looming becomes scalable is 0.003 rad/s [11]. In the driving situations studied here, a similar threshold is evaluated to indicate when the driver decides to use braking.

Personalized Control Algorithm

The parabolic curves (1) and (2) in Figure 12 represent the visual limits on people's awareness of the looming effect. The parameter K in the figure represents the driver's ability to perceive dθ/dt as a function of range and range rate. Below the parabolic curves defined by K, drivers can discern dθ/dt values, hence stress is built up (due to a noticeable closing rate) when dR/dt is negative. Alternatively, stress is relieved when dR/dt is positive (due to a noticeable separation rate). Different drivers have different headway preferences. Also, they differ in their physical ability to discern range-rate or discrepancies in range.

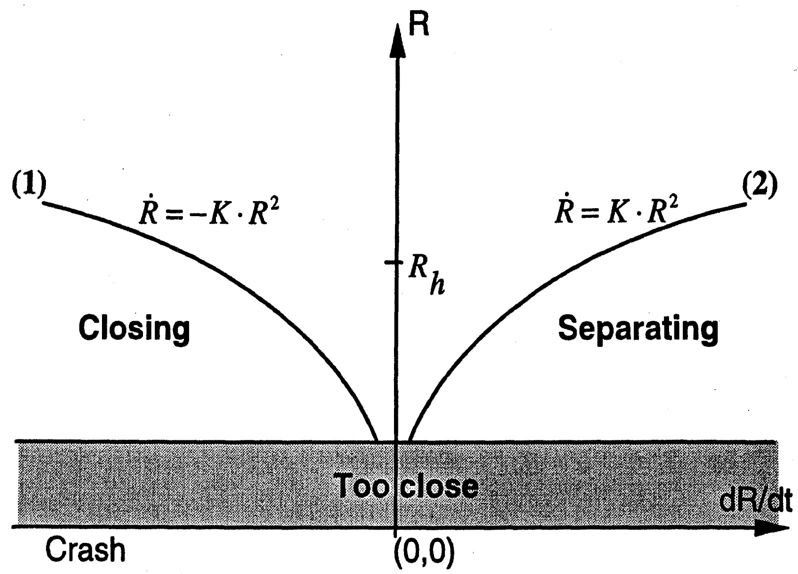


Figure 12. Visual limits on people's awareness of the looming effect

Converting the looming threshold on dθ/dt from the mind's eye coordinates into the [R, dR/dt] space, results in the following nominal constraint on perception:

$$\left|{}^{dR}\!/_{dt}\right| \geq 0.00164R^2 \text{ when using meters } \left(\left|{}^{dR}\!/_{dt}\right| \geq 0.0005R^2 \text{ when using ft}\right) \tag{4.3}$$

When conditions are such that they cause the driver to intervene, the individual's intervention threshold can be identified by observing the brake-application point. The braking level applied by the driver at that point aids in characterizing individual drivers under this simplified approach to modeling braking behavior in manual driving. This analysis method is illustrated in Figure 13.

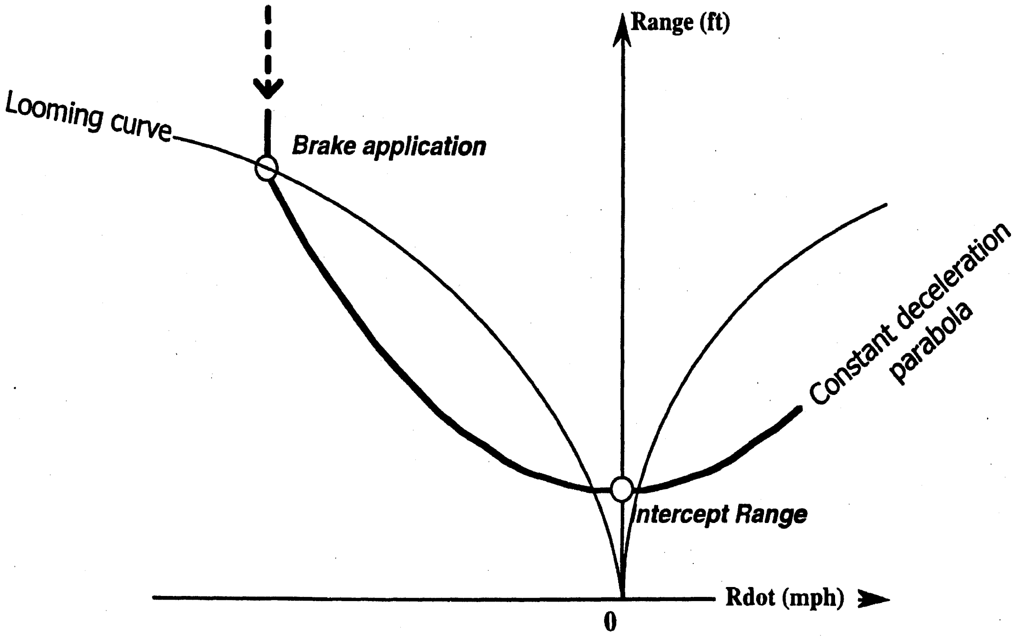


Figure 13. An individuals intervention threshold

Consider a generic closing-from-long-range scenario of headway conflict, where the first (lead) vehicle maintains a constant speed, and the second (following) vehicle approaches from behind, cruising at a higher speed. This results in a constant value of relative velocity (range rate) between the vehicles. The thick line in Figure 13 represents a data stream for this generic headway-conflict scenario, with the dashed upper part representing the initial approach at a constant range rate. When the looming curve is reached, the driver discerns pertinent range and range-rate values, and applies braking. The braking level is determined in such a way so as not to violate the minimum *intercept* range shown in Figure 13.

With the brake application point defined, the looming curve coefficient of a particular driver is given by:

$$K = \frac{\left| dR/dt \right|}{R^2} \tag{4.4}$$

A simplified model was designed to employ the personalized algorithm in the vehicle. The model was based on the following rules (in these rules, location is in terms of range versus range-rate coordinates, as used in Figure 13):

- If the location is above the looming curve, no action is taken.
- If the location is above the coastdown deceleration parabola (a curve such as the thick line in the figure, with a corresponding deceleration level of coastdown), velocity is then controlled by throttle modulation only.

- If the location is below the intercept range, the maximum braking authority is applied.
- If the location is above the intercept range but below both the looming curve and the coastdown deceleration parabola, velocity is then controlled by brake modulation according to equation 5.5.

$$a = \frac{[{dR}/{dt}]^2}{2 \cdot (R - R_{INTERCEPT})} \tag{5.5}$$

The various parameters were established by executing a prescribed set of tests on a test track (see details in Appendix C). The purpose of using proving-grounds conditions was twofold: (1) the ability to stage at a high level of precision and repeatability headway-conflict scenarios for a consistent parameter evaluation, and (2) the participating driver could focus on the task ahead with no distractions. As will be discussed later in the section on results, this second supporting factor for proving-ground testing is also a major drawback of this method, since driving conditions may appear to be too artificial to represent real highway driving.

Subjective Rating and Evaluation

Immediately after exposure to each of the two algorithms (that is, the UMTRI and the personalized algorithms), participants completed a questionnaire regarding their level of comfort with several aspects of the ACC system. A sample questionnaire, used following exposure to either algorithm, is provided in Table 2.

Table 2. Evaluation questionnaire for the ACC with braking control algorithms

1. How similar did this ACC equipped car mimic your car following behavior?

   1 2 3 4 5 6 7

   Dissimilar ... Similar

2. How comfortable did you feel with the following distance provided by this ACC system?

   1 2 3 4 5 6 7

   Uncomfortable ... Comfortable

3. When closing on the preceding vehicle from long range, how similar did this ACC system mimic the way you would have performed the braking?

   1 2 3 4 5 6 7

   Dissimilar ... Similar

4. When the preceding vehicle applied the brakes while you were following at the distance provided by the ACC system, how similar did this ACC system mimic the way you would have performed the braking?

   1 2 3 4 5 6 7

   Dissimilar ... Similar

5. How comfortable would you feel driving with this ACC system on the highway/expressway?

   1 2 3 4 5 6 7

   Uncomfortable ... Comfortable

Simulation Model

Another method for analyzing manual and ACC driving performance that was developed and used during the 4th year is a MATLAB/Simulink™ model. The general structure of the model is depicted in Figure 14. Each of these blocks consists of several internal levels of model blocks. The block entitled "ITT Vehicle Model" is a simplified vehicle model that accepts throttle and brake setting as inputs to compute velocity. The "Information Processor" block contains the control algorithm, and its modular design enables a high level of flexibility in the analysis. During this year, several control schemes were experimented with, and, each time a different control algorithm was designed, it was "plugged" into the Simulink™ model.

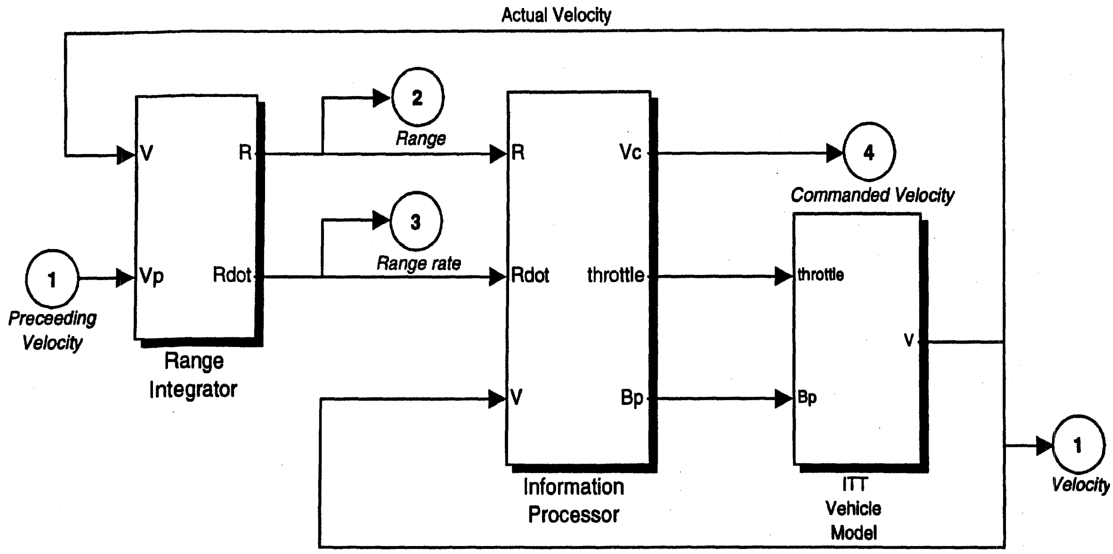


Figure 14. Block diagram of an ACC simulation model

This tool was exercised during a preliminary evaluation of the simplified driver model (the personalized model) and the benchmark model (UMTRI's model). It was also used in a limited way for analyzing results from the proving-ground tests.

4.5 Results

Interpolation Rules for Braking

We successfully tested the special interpolation rules that were developed for gradual braking levels. Analysis of data that were collected indicated that the brakes were applied by the controller in a timely manner. Also, drivers objectively evaluated the UMTRI algorithm favorably, commenting about a smooth transitioning between no-braking, partial-braking, and full-braking operation.

The interpolation rules follow these guidelines (refer to Figure 10):

- the applicable zone is that which is marked "partial braking"
- at each time step "map" the range and range-rate data point on the diagram
- given its range-rate value, a *range ratio* can be computed for the relative location of the data point between the lower parabola (0.22 g) and the upper parabola (0.04 or 0.07 g – depending on the point's location)
- the *range intersection* ($R_{INTERSECT}$) is a point on the vertical axis located between R_{22} and the pertinent other point (R_{07} or R_{04})
- the desired deceleration can now be computed by equation 4.6 (which is a variation of equation 4.5)

$$a = \frac{[Rdot_{data}]^2}{2 \cdot (R_{data} - R_{INTERSECT})} \quad (4.6)$$

Proving-Ground Test Procedures

As a result of the work performed during this year, a set of proving ground tests were devised. Though not comprehensive in the sense of a complete and detailed evaluation of ACC-with-brakes systems, these tests address two fundamental situations of ACC functionality: (1) closing from long range and (2) impeding vehicle decelerating. We view these test as a basis upon which more detailed tests for various ACC-related applications (e.g., crash warning, string stability, etc.) may be developed (Appendix C describes the testing sequence in detail).

Results from the field calculation during the proving-ground testing are provided in Table 3. There are data for eight drivers in this table.

The first line of data for driver 1 indicates that this driver tended to follow at a headway time of approximately 1.20 seconds. The second line indicates a standard deviation of approximately 0.36 seconds of headway time. This represents the driver's preferred following behavior and 1.2 seconds was used in the personalized algorithm for this driver.

Table 3. Field calculations during proving-ground testing

```
SUBJECT 1, 7:55
 ==========================================
  ¥ Mean Th value of  1.20 sec.
  ¥ With StDev of  0.362 sec.
 ==========================================
CLR
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  45.1     3.98     0.088
  ¥ Intercept Range (m)  22.9     1.32     0.058
  ¥ Decel           (g)  0.056    0.013    0.226
  ¥ Looming par. coef. 0.0029   0.0008    0.272

  ¥ Looming curve: Rdot = - 0.0029 * Range^2

LVB
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  29.8     5.57     0.187
  ¥ Intercept Range (m)  13.3     0.25     0.019
  ¥ Decel           (g)  0.104    0.024    0.228
  ¥ Looming par. coef. 0.0029   0.0006    0.197

  ¥ Looming curve: Rdot = - 0.0029 * Range^2

Used: Ri=23, Coeff=0.0029

SUBJECT 2, 9;00
 ==========================================
  ¥ Mean Th value of  0.93 sec.
  ¥ With StDev of  0.073 sec.
 ==========================================
CLR
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  44.9     3.57     0.080
  ¥ Intercept Range (m)  22.1     2.93     0.133
  ¥ Decel           (g)  0.079    0.021    0.270
  ¥ Looming par. coef. 0.0036   0.0002    0.051

  ¥ Looming curve: Rdot = - 0.0036 * Range^2

LVB
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  29.1     9.83     0.337
  ¥ Intercept Range (m)  20.6     1.13     0.055
  ¥ Decel           (g)  0.038    0.044    1.166
  ¥ Looming par. coef. 0.0005   0.0002    0.379

  ¥ Looming curve: Rdot = - 0.0005 * Range^2

Used: Ri=22, Coeff=0.0036
```

```
SUBJECT 3, 10:00
 ==========================================
  ¥ Mean Th value of  1.93 sec.
  ¥ With StDev of  0.829 sec.
 ==========================================
CLR
                         mean     stdDev  stdDev/mean
  ¥ Brake Range     (m)  61.8     12.30     0.199
  ¥ Intercept Range (m)  44.2      6.26     0.141
  ¥ Decel          (g)  0.055    0.020     0.367
  ¥ Looming par. coef. 0.0014   0.0002     0.140

  ¥ Looming curve: Rdot = - 0.0014 * Range^2

LVB
                         mean     stdDev  stdDev/mean
  ¥ Brake Range     (m)  62.9      1.06     0.017
  ¥ Intercept Range (m)  51.0      1.20     0.024
  ¥ Decel          (g)  0.074    0.026     0.355
  ¥ Looming par. coef. 0.0004   0.0002     0.456

  ¥ Looming curve: Rdot = - 0.0004 * Range^2

Used: Ri=45, Coeff=0.0014

SUBJECT 4, 11:10
 ==========================================
  ¥ Mean Th value of  3.41 sec.
  ¥ With StDev of  0.555 sec.
 ==========================================
CLR
                         mean     stdDev  stdDev/mean
  ¥ Brake Range     (m) 110.0      3.25     0.030
  ¥ Intercept Range (m)  50.5     71.42     1.414
  ¥ Decel          (g)  0.071    0.060     0.855
  ¥ Looming par. coef. 0.0002   0.0001     0.806

  ¥ Looming curve: Rdot = - 0.0002 * Range^2

LVB
  (* ZB: Never got to intercept *)

Used: Ri=48, Coeff=0.0002
```

```
SUBJECT 5, 13:10
 =========================================
  ¥ Mean Th value of  1.87 sec.
  ¥ With StDev of  0.175 sec.
 =========================================
CLR
                          mean     stdDev  stdDev/mean
  ¥ Brake Range      (m)  91.5      5.17     0.057
  ¥ Intercept Range (m)  30.5      7.24     0.237
  ¥ Decel            (g)  0.016    0.002     0.115
  ¥ Looming par. coef. 0.0006   0.0001     0.179

  ¥ Looming curve: Rdot = - 0.0006 * Range^2

LVB
                          mean     stdDev  stdDev/mean
  ¥ Brake Range      (m)  72.0      5.27     0.073
  ¥ Intercept Range (m)  36.9      2.80     0.076
  ¥ Decel            (g)  0.053    0.001     0.028
  ¥ Looming par. coef. 0.0002   0.0002     0.776

  ¥ Looming curve: Rdot = - 0.0002 * Range^2

Used: Ri=30, Coeff=0.0006

SUBJECT 6, 14:20
 =========================================
  ¥ Mean Th value of  2.46 sec.
  ¥ With StDev of  0.242 sec.
 =========================================
CLR
                          mean     stdDev  stdDev/mean
  ¥ Brake Range      (m) 106.5      2.83     0.027
  ¥ Intercept Range (m)  18.8     26.59     1.414
  ¥ Decel            (g)  0.013    0.003     0.222
  ¥ Looming par. coef. 0.0003   0.0000     0.179

  ¥ Looming curve: Rdot = - 0.0003 * Range^2

LVB
                          mean     stdDev  stdDev/mean
  ¥ Brake Range      (m)  64.1      1.98     0.031
  ¥ Intercept Range (m)  55.0     11.60     0.211
  ¥ Decel            (g)  0.027    0.038     1.414
  ¥ Looming par. coef. 0.0002   0.0002     0.867

  ¥ Looming curve: Rdot = - 0.0002 * Range^2

Used: Ri=50, Coeff=0.0002
```

```
SUBJECT 7, 15:30
 ========================================
  ¥ Mean Th value of  1.73 sec.
  ¥ With StDev of  0.095 sec.
 ========================================
CLR
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  47.2    10.56     0.223
  ¥ Intercept Range (m)  25.3     9.56     0.378
  ¥ Decel            (g)  0.062    0.024     0.384
  ¥ Looming par. coef. 0.0032   0.0018     0.559

  ¥ Looming curve: Rdot = - 0.0032 * Range^2

LVB
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  37.3    11.78     0.315
  ¥ Intercept Range (m)  19.7     4.02     0.204
  ¥ Decel            (g)  0.097    0.035     0.362
  ¥ Looming par. coef. 0.0020   0.0009     0.468

  ¥ Looming curve: Rdot = - 0.0020 * Range^2

Used: Ri=25, Coeff=0.0032

SUBJECT 8, 16:40
 ========================================
  ¥ Mean Th value of  1.26 sec.
  ¥ With StDev of  0.122 sec.
 ========================================
CLR
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  43.1     9.52     0.221
  ¥ Intercept Range (m)  18.6     4.30     0.231
  ¥ Decel            (g)  0.034    0.028     0.821
  ¥ Looming par. coef. 0.0015   0.0008     0.520

  ¥ Looming curve: Rdot = - 0.0015 * Range^2

LVB
                          mean    stdDev  stdDev/mean
  ¥ Brake Range      (m)  39.5    10.20     0.258
  ¥ Intercept Range (m)  15.3     3.88     0.255
  ¥ Decel            (g)  0.076    0.021     0.272
  ¥ Looming par. coef. 0.0022   0.0005     0.244

  ¥ Looming curve: Rdot = - 0.0022 * Range^2

Used: Ri=19, Coeff=0.0015
```

Similar headway time results were recorded for each driver. Six of the drivers used headway times between approximately 1 and 2 seconds. See Table 3. However, driver 4, who is an older male, used approximately 3.4 seconds and driver 6, who is a middle-aged female, chose approximately 2.5 seconds. These long headway times were not anticipated based upon past experience with lay drivers operating on freeways. We believe that these drivers were reacting to the test track environment, and they may not have been driving normally. In any event, the curves at each end of the oval track are not suitable for following at headway times greater than 2 seconds. As a result, drivers 4 and 6 drove the ACC systems with 2 second headway. This probably means that their subjective results are questionable as will be seen later. For the other six drivers we set headway times for ACC within the nearest 0.2 seconds of the value they used in manual following.

Following the CLR heading for each driver, there are four parameters listed in Table 3. These parameters pertain to the driver's behavior when steadily closing on a slower moving vehicle. The brake range is the range at the time that the driver applied the brakes. The intercept range is the range at the time when Rdot went through zero due to the braking effort applied by the driver. Decel is the average deceleration between the time when the driver applied the brakes and the time when Rdot reached zero. This means that decel is calculated by dividing the change in velocity by the time interval involved. The looming parameter pertains to when the driver decides to brake. As explained earlier, it is based upon the hypothesis that drivers decide to brake when they feel that they are closing at a relative speed that is too great for the distance between vehicles. (See the material presented in conjunction with figure 4 in the previous section.) In this sense, the target is growing in visual angle at a rate that exceeds the driver's level of comfort associated with looming of the image. This coefficient appears in the looming curve used for each driver as listed in Table 3.

There is also similar data under the heading LVB (lead-vehicle-braking) in Table 3. In this case, LVB stands for lead vehicle braking. The test conditions for the lead-vehicle-braking test involve the two vehicles proceeding at approximately the driver's preferred headway time with Rdot approximately equal to zero. Then the lead vehicle suddenly decelerates such that the driver of the following vehicle will need to intervene. The level of braking deceleration and the conditions at which the driver decides to brake are determined for this scenario also. For example, driver 1 happens to attain the same looming curve for both tests, but the intercept range for Rdot equal to zero is 22.9 m in the CLR (closing range test) as opposed to 13.3 m in the LVB test. Inspection of the table shows that the results differ considerably from driver to driver.

The looming curve determined when the brakes will be applied in the personalized algorithm for each driver. The level of braking was calculated using the point on the looming curve at brake application and the value of intercept range for that person. This information is used to compute the level of steady deceleration needed to go from the brake application point to the intercept range for that driver. This is the level of deceleration used in the personalized algorithm. The parameters Ri (intercept range) and Coeff (looming coefficient) as used in determining braking behavior in the personalized algorithm for each driver are listed after the term Used: in Table 3.

Subjective Ratings and Evaluation

We believe that our procedures produced reasonable results for drivers number 1, 2, 3, 5, 7, and 8. However, the looming coefficients for drivers 4, 5, and 6 appear to be very small. These drivers put on the brakes at relatively long ranges. The intercept ranges for drivers 3, 4, and 6 are relatively long also. Nevertheless, the subjective ratings of the UMTRI algorithm were relatively high for all drivers. (See Table 4.) The top line in the table lists the drivers number, coded with age and gender (male/female and young/middle-aged/old). The last two columns include the compiled mean responses of all the drivers to the seven-point scale for the two algorithms. While the subjective assessments were largely favorable, participants did report the UMTRI algorithm to be preferable or more similar to their own braking behavior.

Table 4. Subjective ratings, specific to test conditions

	1 MM		2 MM		3 MF		6 FM		4 MO		5 MO		7 MO		8 FY		ALL	
	UMTRI	Personalized	UMTRI	Personalized	UMTRI	Personalized	UMTRI	Personalized	UMTRI	UMTRI	UMTRI	Personalized	UMTRI	Personalized	UMTRI	Personalized	UMTRI	Personalized
Q1 mimic following	6	6	5	6	5	5	5	1	6	3	7	6	6	7	6	6	5.75	5.00
Q2 comfort in following	6	6	6	5	5	6	4	4	5	3	7	7	7	7	7	7	5.87	5.62
Q3 mimic closing	7	7	5	6	5	4	5	3	3	2	5	5	6	7	5	7	5.12	5.12
Q4 mimic lead-vehicle braking	7	5	4	4	2	5	5	1	4	2	5	5	7	7	7	7	5.12	4.50
Q5 comfort of highway driving	6	5	6	6	5	5	5	3	6	4	7	7	7	7	7	7	6.12	5.50

The subjective ratings of the personalized algorithm for drivers 4 and 6 were low. This evidence supports the idea that drivers are sensitive to deviations from the headway times they like. These were the drivers given 2.0 second headway time instead of 3.4 and 2.5 seconds.

On the other hand, the other drivers rated their personalized algorithms favorably. Driver 7 gave his personalized algorithm all sevens and driver 8 gave her personalized algorithm four sevens and one six.

The main result that we want to emphasize is that the subjective ratings for comfort in highway driving are generally positive. The mean of the ratings for the UMTRI ACC-with-braking algorithm was 6.12 out of a possible 7. Although drivers 4 and 6 did not rate their personalized algorithms highly, the overall mean rating for the personalized algorithms was 5.5. In general, the drivers felt that they would be comfortable using these ACC-with-braking systems in highway driving.

The drivers were asked to extrapolate their experience to consider whether they would like a warning signal for intervention and whether they would like stronger braking. There was a wide range of opinions on both issues with the mean value being 4.6 for both issues (with 7 representing the most favorable end of the scale for both issues). This indicates that these results are non-conclusive.

Finally the drivers were asked to state how they decided to intervene by braking when using the ACC-with-braking system. The results are tabulated in Table 5.

Table 5. Decision basis for intervening on ACC-with-braking

Driver	Decision Basis
1 male middle-aged	Distance (range)
2 male middle-aged	Driving style
3 female middle-aged	Too close (range)
6 female middle-aged	Distance (range)
4 male older	No interventions
5 male older	No interventions
7 male older	Two car lengths (range)
8 female younger	Closing speed (range rate)

The results in Table 5 are interesting in that they appear to indicate that drivers believe that range is a major factor in making the decision to brake. The subjective results in Table 1 tend to support the view that drivers will be satisfied if the following headway time and the intercept range match their driving style. (Incidentally, it is not clear what driver 2 meant by the term "driving style" but perhaps it is the same as our meaning in this context.) One driver did mention closing rate, which relates to the looming effect. However, it does not appear that lay drivers are versed in the use of the term looming.

4.6 Fourth Year's Conclusions and Recommendations

Proving Grounds Test

Proving grounds test are fine for checking out vehicle and control system properties. However, we found that some people did not behave in ways that are typical of highway driving. They appear to be influenced by the test track environment. In this work, two out of eight drivers became very conservative when driving on an oval test track with 916 foot radius curves on either end.

With regard to testing on the highway, however, the proving ground experience was a necessary step. The drivers' favorable ratings of these ACC-with-braking systems provided evidence supporting the proposition that freeway operation with lay drivers would be reasonable if the drivers were accompanied by knowledgeable researchers. In addition, the driving exercises on the proving grounds allowed the researchers (both human factors and vehicle dynamics and control engineers) to see how the lay drivers reacted to systems' braking properties. It was observed that the drivers understood how the systems worked. They were able to supervise the systems. They were ready to intervene if they were uncomfortable with the situation. The use of the foundation brakes did not confuse the drivers nor did it make them uncomfortable. Based upon this experience, the researchers felt comfortable in recommending that plans be made to conduct ACC-with-braking tests on the highway with lay drivers in the next year of the FOCAS project.

The original plans for the proving ground testing involved 12 drivers. This number was picked to provide a basis for assessing the influences of gender and driver age on the results. However, it was decided that the proving ground was not the place to study these factors. Driver influences on system use need to be studied in real traffic. Otherwise, it will be difficult to extrapolate from the proving ground results to highway behavior.

Proving ground tests of lay drivers may require special attention because some lay drivers are greatly influenced by the test track environment. Unless the influence of the test track environment is taken into account, proving ground tests for determining driver characteristics are not recommended.

Six of the eight drivers appeared to be relatively uninfluenced by the test track environment. These drivers rated both the UMTRI and their personalized algorithm favorably. Examination of the subjective results for these drivers indicates that drivers are critically sensitive to the range to the preceding vehicle. Individual drivers have individual preferences. If these preferences are met by the ACC system, drivers will rate the system favorably. This is further evidence that headway time gap needs to be adjustable in order to satisfy driver preferences.

Examination of the results to reach conclusions regarding the looming effect is not as clear. We still believe that looming has an important role in manual control of the headway time gap. However, the results do not appear to provide us with startling new breakthroughs. One pertinent observation is that, if the intercept range in braking is reasonably close to the driver's preferences, the driver will rate the ACC system favorably. Apparently, the intercept ranges chosen for the UMTRI algorithm are close enough to the driver's preferences to allow the driver's to give favorable subjective ratings.

In summary, there are good and bad aspects to proving ground tests.
The good aspects are

- the ability to stage headway-conflict scenarios at a high level of precision and repeatability, and
- the participating driver can focus on the task ahead with no distractions.

The bad aspects are

- the driving conditions are too artificial to represent real highway operation since the participating driver has no constraints and influences as determined by the presence of the traffic stream, and hence
- the proving ground environment does not provide the proper context within which to evaluate the utility of driver assistance systems.

Algorithm Design

The interpolation method used to introduce braking to the ACC design was found to be both practical and agreeable for the drivers. The combination of flexible parametric design with smooth and gradual brake application provide for ample tuning capacity for design optimization. It was recommended that this design approach be adopted in future ACC-with-braking research work.

Augmenting the deceleration algorithm so that it considered deceleration by the preceding vehicle was found to be satisfactory. It was recommended that in the future, provisions are made for tuning the amount and timing of the response, so that individual driver's preferences are met.

5.0 Year Five Report

This section reports on the activities during year 5 of the FOCAS program. Provided below is a horizontal review summarizing these activities.

ACC SYSTEM CONFIGURATION	RESEARCH ACTIVITIES	ANALYSIS METHODOLOGY	RESULTS	FINDINGS AND RECOMMENDATIONS
◆ Same configuration of ACC with braking as in the 4th year ◆ Revised control algorithms for throttle and brake actuation ◆ Improved acceleration response ◆ Preceding vehicle deceleration used in the braking portion of the ACC algorithm ◆ System with NHTSA warning concept ◆ Time-to-impact warning system ◆ System with desired-deceleration warning	◆ Tested lay drivers using ACC with braking on freeways ◆ Developed an experimental design for freeway testing using age and gender as independent variables ◆ Tuned the braking algorithm to respond comfortably to rapid closing and/or preceding-vehicle braking ◆ Developed procedures for studying braking latency ◆ Developed procedures for identifying lane changes ◆ Developed further the NHTSA collision-warning concept ◆ Developed desired deceleration collision-warning concept ◆ Developed further the time-to-impact collision-warning concept ◆ Analyzed crash warning algorithms ◆ Studied intervention vigilance and ACC deceleration authority	◆ Conducted knowledge discovery in the ACC-with-braking database ◆ Statistically analyzed for significance of test results ◆ Processed FOT data to study braking latency and lane changing ◆ Analyzed the NHTSA crash warning concept ◆ Investigated different "data cleansing" methods for FCW ◆ Evaluated various FCW algorithms ◆ Studied FCW algorithms with respect to situation awareness ◆ Analyzed intervention vigilance vs. ACC deceleration authority	◆ Delivered database of ACC-with-braking measurements to NHTSA ◆ Found statistically significant differences by age and gender among the lay test drivers ◆ Found evidence of differences between manual and ACC driving ◆ Completed report on braking latency and lane changing ◆ Made discoveries concerning the influences of incorporating braking into ACC ◆ Demonstrated that braking events are complex and multidimensional ◆ Reported a NHTSA FCW algorithm for all inter vehicle relationships ◆ Compared results on three FCW systems ◆ Related vigilance requirements to deceleration authority	◆ ACC systems with braking will be enjoyable to use for most drivers ◆ Development of collision-warning systems should consider that drivers brake for reasons of headway-time margin, closing rate, and preceding vehicle deceleration ◆ Collision-warning systems must consider idiosyncrasies of the sensor ◆ Research and development is needed for optimizing algorithms based on the NHTSA concept ◆ Braking activity provides one indicator of a driver's situation awareness ◆ The NHTSA FCW algorithm tends toward a request for emergency action ◆ The Ttc warning is primarily a situation awareness prompt ◆ The VcDot algorithm combines both situation awareness and emergency concerns ◆ ACC-with-braking will provide a reduction in the workload associated with headway-keeping

The work in year 5 was divided into five separate, major research tasks. Accordingly, section 5 of this report is organized into five subsections corresponding to these major research tasks. These subsections and tasks are as follows:

Evaluation of ACC-with-braking (Freeway testing with lay drivers)

The objectives of this research task were:

a) Evaluate the operational performance of a "basic" ACC-with-braking function in freeway driving,

b) Identify how results from driving with ACC-with-braking differs from the FOT results for an ACC system with approximately 0.07 g of deceleration authority, and

c) Examine operational performance issues associated with the braking capability as implemented in our "basic" ACC-with-braking function.

The following questions were addressed in pursuit of these objectives:

1. How well does ACC-with-braking achieve its functional goals?
2. What are the differences in driver behavior between accompanied and unaccompanied driving?
3. How do the FOT and FOCAS data compare?
4. What are the driving characteristics occurring when the ACC system is braking? In addition, how do these characteristics compare to those observed in manual driving?
5. When do drivers decide to brake and when do they decide to intervene on ACC-with-braking?
6. What is the relative frequency of driver intervention as a function of the level of deceleration authority for ACC-with-braking?

Braking latency

During the fifth year, two special tasks were identified and prescribed. These tasks involved processing ICC FOT data to study braking latency and driver lane changing behavior. A separate report on these subjects was written and delivered to NHTSA. Certain results from the study of braking latency are reported here. These results provide information on situations in which both the preceding and equipped vehicles decelerated at levels greater than 0.1 g. These data have provided the basis for evaluating forward crash warning algorithms. (See section 5.4.)

NHTSA's warning algorithm

This task involved analyzing a crash warning algorithm that is of special interest to NHTSA. The warning issued by this algorithm calls for emergency braking upon the part of the driver. Different methods of data directing for the algorithm and programming the algorithm were studied. The influences of sensor characteristics were investigated. A Kalman filter approach was developed and used in the final version of the warning algorithm. This report provides documentation on the algorithm developed in this task.

Evaluation of FCW systems

Three different types of FCW systems were examined in this task. The ICC FOT data identified and employed in task 5.2 were employed as inputs to the respective algorithms. The names and type of FCW system are as follows:

- NHTSA algorithm — This has an emergency braking goal.
- Tti algorithm — This has a situation awareness goal.
- Vcdot algorithm — This has both situation awareness and crash avoidance aspects.

The results provide insights into when these different types of FCW systems would warn the driver.

Vigilance versus deceleration authority

Finally, an analysis of FOT cases of driver braking intervention was performed as a means of estimating the influence of ACC deceleration authority on the frequency of brake intervention and, by implication, the potential for lapses in driver vigilance over long periods of sustained ACC engagement.

Each subsection is organized with the following generalized format in mind:

- Research Activities
- Analysis Methodology
- Results
- Findings and Recommendations

5.1 Evaluation of ACC-with-braking (Freeway testing with lay drivers)

5.1.1 Introduction

5.1.1.1 ACC Configuration

During the 5th year we used the same test-vehicle and ACC-system hardware that were used during the 4th year. The only change to the hardware configuration in the 5th year was an addition of a buzzer to study crash-warning alarm features and design.

The system was refined and revised in accordance with the recommendations from year 4. In addition, development efforts with various system configurations focused on preparing the vehicle for

- lay drivers operating the ACC-with-brakes system on the highway, and
- investigation by researchers of crash-warning algorithms.

5.1.1.2 Revised Throttle and Brake Control Algorithms

Improved Acceleration

One of the main complaints drivers had with regard to the behavior of the vehicle under ACC operation was poor longitudinal acceleration. The subject was first raised during the ICC FOT [1], but the level of dissatisfaction was increased when brakes were incorporated into the design of the system. The added deceleration authority magnified the lack of acceleration authority. In the course of investigating ways to remedy the problem, it was discovered that the engine controller responds differently to commands via software than it does to commands via hardware. That is, the response of the Chrysler throttle control to speed commands sent from the ACC controller, such as it was in the system design of the ICC FOT fleet, as well as in the design of this ACC-with-brakes system, is much slower than the throttle's response to depressing the "Accel" button on the steering wheel. Chrysler engineers confirmed this observation. However, no solution was offered because it was not feasible to modify the software of the engine controller within a reasonable effort. Therefore, UMTRI designed a special electronic circuit to mimic the cruise-control buttons being pressed, so that when the ACC control algorithm determined that the vehicle should speed up, the circuit was activated, thus resulting in a significantly more responsive system.

Responding to Preceding-Vehicle Deceleration

The configurations studied in the 5th year involved directly responding to braking by the lead vehicle. The commanded deceleration was previously computed based on the location of the range and range-rate data in the space defined by these coordinates (see figure 10 of year 4). By incorporating a term to account for the deceleration of the lead vehicle ($\dot{V}_p$) in the command equation, the ACC system could respond more directly to speed changes of the lead vehicle. This feature is described by an equation of the following form:

$$D_c = K1 \cdot D_{location} + K2 \cdot \dot{V}_p \qquad (5.1)$$

where D_c is the deceleration command to the smart booster, K1 and K2 are adjustable proportioning parameters, and $D_{location}$ is the component of the deceleration command based on the location in the range and range-rate space.

5.1.2 Research Activities

5.1.2.1 Brake Algorithm Variations

During the first part of year 5, we used our simulation tools to investigate a variety of braking algorithms. We found that an approximate differentiator could provide a useful estimate of $\dot{V}_p$ for control purposes. Hence we incorporated a $\dot{V}_p$ feature in our braking algorithm. This means the algorithm used in year 5 responds to preceding (impeding) vehicle deceleration as well as to small range and/or range-rate (where small range-rate means large negative values of range-rate). Previously in year 4, constant deceleration parabolas were used as the exclusive algorithmic feature for controlling response to small range and range-rate whether or not the impeding vehicle was decelerating. The latest system uses a combination of both the parabolas and the $\dot{V}_p$ feature in the braking part of the ACC control algorithm (see equation 5.1 above).

During the fifth year, the new features were tried, evaluated, adjusted, and rated useful by human factors experts and vehicle dynamics and control engineers.

5.1.2.2 Freeway Testing of Lay Drivers

We set up the ACC-with-braking car for tests with driver subjects. This system responds to the deceleration of the preceding vehicle. If the car ahead brakes suddenly at over 0.1 g, the ACC car decelerates at least at the same rate as the preceding vehicle up to a maximum deceleration of 0.2 g.

Before testing, system level issues associated with ACC-with-braking were resolved. Parameters were selected that determine when the brakes will be applied. The algorithmic rules for brake application cover situations when the preceding vehicle is too close and/or when the preceding vehicle is decelerating.

Experimental Design Development

All of the logistical activities associated with selecting lay drivers and obtaining Human Use Review Panel (HURP) approval were completed. The experimental design was determined. Twenty-four licensed drivers were recruited for this study from a list of potentially interested participants maintained by the Human Factors Division at UMTRI. Drivers from three age groups – young, middle-aged, and older (20-30, 40-50 and 60-70 years of age) – participated. Within each age group, participation was balanced for gender. Only individuals who were reportedly regular users of conventional cruise control were recruited. In addition, each participant was required to have a valid, unrestricted, driver's license. Participants received $35 for taking part in the study.

Some background information about participants was also gathered. The mean age for the young group was 23.8, for the middle-aged group 47.1, and for the older group the mean age was 67.8. The means of driving experience (years) and annual mileage (miles) were 7.3 – 8250, 30.8 – 18375, and 49.6 – 11286 for the young, middle-aged and older groups, respectively.

Upon arrival at UMTRI, drivers were asked to read an introductory letter that provided a description of ACC with braking, and to give their written consent to participate in the study. Each participant viewed a ten-minute training video detailing the functionality of the ACC system and its components. Next, each driver was shown the ACC-equipped vehicle, and special attention and instruction was given to the sensors, displays, and controls. Participants were given the opportunity to ask questions before embarking on the route. A short break at the UMTRI facility was provided between trips, with each trip lasting approximately 75 minutes. At the completion of the test drive the participants completed a detailed questionnaire about their experience with the ACC system (See Appendix D).

As shown in Figure 15, each participant drove a 72-mile route, consisting predominantly of expressways and state highways in the Detroit metropolitan area. The same route was traversed twice, once driving manually and once driving with the ACC system engaged. The order in which participants experienced the manual or ACC condition was balanced across gender and age groups. Participants were accompanied by an experimenter who rode along in the front seat to assist with navigating and to answer any questions about the ACC system operation. Drivers were instructed to drive as they normally would. Testing was only performed under dry roadway and daylight conditions. In addition, testing was only conducted under non-peak traffic conditions (9:30 am –

12:00 pm or 1:30 pm – 4:00 pm). The route selected was generally free of construction, although a few minor adjustments in the end of the route were made over the course of data collection to accommodate roadway construction.

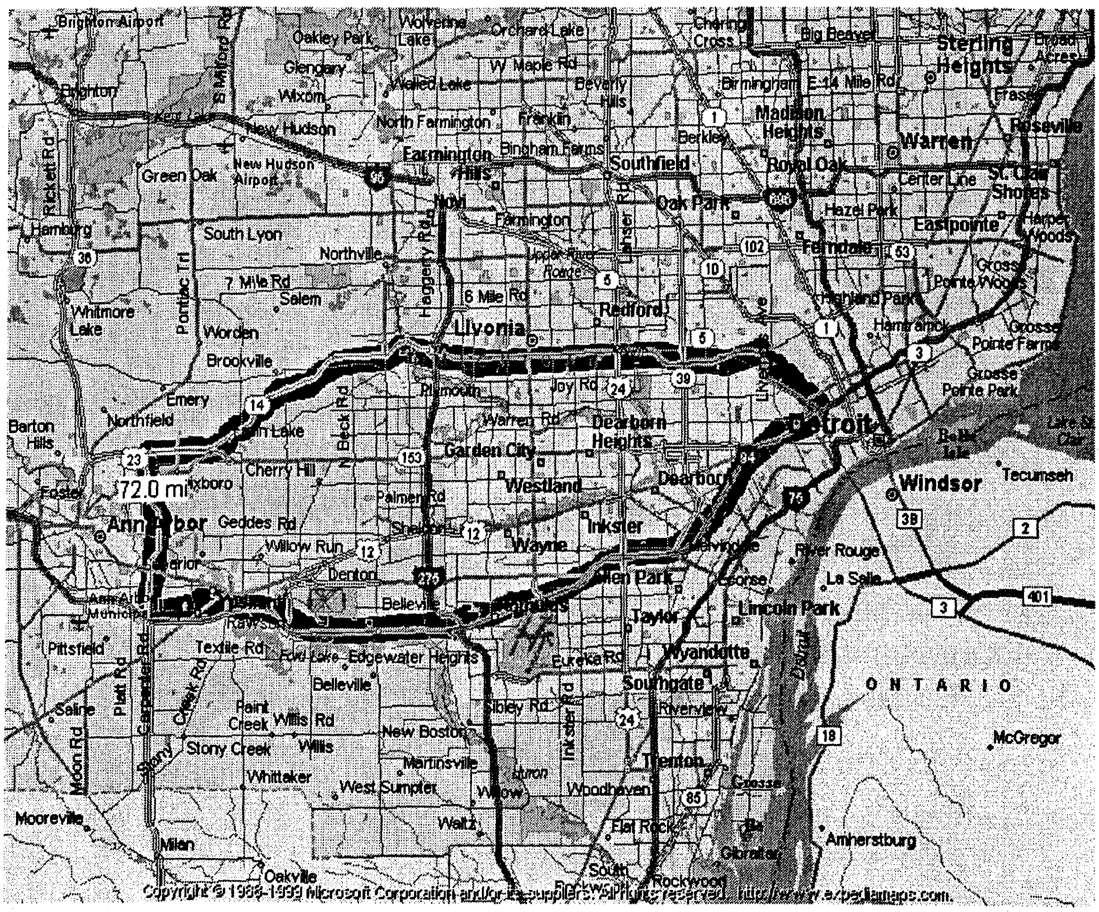


Figure 15. Map of the test route

5.1.3 Analysis Methodology

5.1.3.1 Statistical Analysis of Lay-Driver Data

Analysis of data from questionnaires

Each participant completed a questionnaire consisting of 43 questions. Four of the questions were of the free response form and the remaining 39 questions employed Likert-type scales ranging from 1 to 7. An analysis of variance (ANOVA) was performed on each of the Likert-type questions with age group (young, middle-aged, and older) and gender (male and female) as independent variables. Several questions also had driving mode as a within-subject independent variable. When a main effect or interaction had more than two levels, a Newman-Keuls post-hoc analysis of the differences between means was performed.

Statistical analysis of objective data pertaining to lay drivers

A series of analyses of variance (ANOVA) were performed using the mean values for each participant where the dependent measures for the separate analyses were range, range-rate, headway-time-margin and velocity, for speeds greater than 55 mph. There were two between-subjects independent variables, participant age and participant gender, and one within-subject independent variable, mode of driving for the trip (manual vs. ACC routes) in each ANOVA. When a main effect or interaction had more than two levels, a Newman-Keuls post-hoc analysis of the differences between means was performed.

5.1.3.2 Knowledge Discovery and Data Mining

Following the tests with lay drivers, a database was constructed containing the objective data and the subjective evaluations. The objective data were examined using our ad hoc data mining methods, which constitute an informal approach for discovering knowledge in databases. This approach uses the insight of experts with a-priori knowledge pertaining to driver factors, vehicle dynamics, and control methods.

5.1.3.3 Simulation Analysis of ACC-With-Braking Systems

The simulation capabilities developed in the previous year were used to analyze the ACC-with-braking system (see Analysis Methodology section of year 4.). This analysis was focused primarily on evaluating the predicted system's behavior during the pre-launch stages of highway testing with lay drivers.

5.1.4 Results

5.1.4.1 Subjective Results from Freeway Driving the ACC-with-braking Vehicle

Of the 39 Likert-type questions, there were eight in which statistically significant results were observed. The results of the ANOVAs are provided with the associated questions, means tables with confidence intervals, and Student-Newman-Keuls post-hoc analyses where appropriate. Summary statistics are provided in Appendix D for all remaining questions.

The results to question 6 show that young and middle-aged drivers felt safer driving manually than they did driving with ACC, but that older drivers felt safer when driving with ACC as opposed to manual control. Overall each of the age groups felt relatively safe driving in the ACC mode. The same is true for the participant's sense of comfort. Specifically, the results of question 7 show that all participant groups felt relatively comfortable with either mode of operation, with the possible exception of middle-aged females.

Question 6. How safe did you feel while driving in each of the following modes of operation?

	1	2	3	4	5	6	7
Manual Control	1 Very Unsafe	2	3	4	5	6	7 Very Safe
ACC	1 Very Unsafe	2	3	4	5	6	7 Very Safe

A statistically significant interaction was observed between participant age and driving mode, $F(2,18) = 4.013, p = .036$.

		Mean	Std. Error	95% Confidence Interval	
AGE	MODE			Lower Bound	Upper Bound
Young	Manual	6.875	.250	6.350	7.400
	ACC	6.125	.280	5.538	6.712
Middle-Aged	Manual	6.125	.250	5.600	6.650
	ACC	5.625	.280	5.038	6.212
Older	Manual	5.750	.250	5.225	6.275
	ACC	6.375	.280	5.788	6.962

	Mean			
Middle-Aged ACC	5.625	A		
Older Manual	5.75	A		
Middle-aged Manual	6.12	A	B	
Young ACC	6.12	A	B	
Older ACC	6.375		B	
Young Manual	6.875			C

Means with the same letter are not significantly different from one another.

Question 7. How comfortable were you while driving in each of the following modes of operation?

	1	2	3	4	5	6	7
Manual Control	1 Very Uncomfortable	2	3	4	5	6	7 Very Comfortable
ACC	1 Very Uncomfortable	2	3	4	5	6	7 Very Comfortable

A statistically significant interaction was observed for participant age and participant gender, $F(2,18) = 3.909, p = .039$.

		Mean	Std. Error	95% Confidence Interval	
GENDER	AGE			Lower Bound	Upper Bound
Female	Young	6.500	.339	5.789	7.211
	Middle-Aged	5.375	.339	4.664	6.086
	Older	6.125	.339	5.414	6.836
Male	Young	6.000	.339	5.289	6.711
	Middle-Aged	6.625	.339	5.914	7.336
	Older	5.875	.339	5.164	6.586

	Mean		
Middle-Aged Female	5.375	A	
Older Male	5.875	A	
Young Male	6.0	A	B
Older Female	6.125	A	B
Young Female	6.5		B
Middle-Aged Male	6.625		B

Means with the same letter are not significantly different from one another.

The results to question 8 clearly show that participants reported driving with ACC to be significantly more convenient than driving manually, under similar conditions. The difference in rating of convenience between ACC and manual control was greatest for the youngest and oldest participants, with the middle-aged participants being almost indifferent to either mode of operation.

Question 8. How convenient did you find driving in each of the following modes of operation?

Manual Control	1	2	3	4	5	6	7
	Very Inconvenient						Very Convenient
ACC	1	2	3	4	5	6	7
	Very Inconvenient						Very Convenient

The statistically significant main effect was driving mode, $F(1, 18) = 13.292$, $p = .002$.

	Mean
Manual	5.208
ACC	6.208

A statistically significant interaction was observed for participant age and driving mode, $F(2, 18) = 5.054, p = .018$.

		Mean	Std. Error	95% Confidence Interval	
AGE	MODE			Lower Bound	Upper Bound
Young	Manual	4.500	.346	3.773	5.227
	ACC	6.500	.341	5.783	7.217
Middle-Aged	Manual	6.000	.346	5.273	6.727
	ACC	5.875	.341	5.158	6.592
Older	Manual	5.125	.346	4.398	5.852
	ACC	6.250	.341	5.533	6.967

	Mean			
Young Manual	4.5	A		
Older Manual	5.125		B	
Middle-Aged ACC	5.875			C
Middle-Aged Manual	6.0			C
Older ACC	6.25			C
Young ACC	6.5			C

Means with the same letter are not significantly different from one another.

A statistically significant interaction was observed for participant age and participant gender, $F(2, 18) = 3.812, p = .04$.

		Mean	Std. Error	95% Confidence Interval	
GENDER	AGE			Lower Bound	Upper Bound
Female	Young	5.750	.351	5.012	6.488
	Middle-Aged	5.375	.351	4.637	6.113
	Older	6.000	.351	5.262	6.738
Male	Young	5.250	.351	4.512	5.988
	Middle-Aged	6.500	.351	5.762	7.238
	Older	5.375	.351	4.637	6.113

	Mean			
Young Male	5.25	A		
Middle-Aged Female	5.375	A		
Older Male	5.375	A	B	
Young Female	5.75	A	B	
Older Female	6.0		B	C
Middle-Aged Male	6.5			C

Means with the same letter are not significantly different from one another.

In response to question 10, there was a significant difference in that young participants reported driving slower in the ACC mode, relative to manual control, than either the middle-aged or older participants. However, as will be seen in the results to the objective data on participant velocities, it was not the case that young participants drove slower in the ACC mode. In fact, all three age groups drove slightly, though not significantly, faster in ACC – with mean velocities of 98.8 ft/s in ACC verses 97.9 ft/s in manual, collapsed across all participants.

Question 10. How fast did you drive when using the ACC system, as compared to driving manually?

1	2	3	4	5	6	7
Slower than manual						Faster than manual

The statistically significant main effect was age, $F(2, 18) = 9.54, p = .003$.

	Mean		
Young	2.75	A	
Middle-aged	4.25		B
Older	4.88		B

Means with the same letter are not significantly different from one another.

In response to question 20, older participants reported feeling that they did not understand what the ACC system was doing, or how it might behave, significantly more frequently than did either the young or middle-aged participants. None the less, the mean response to question 20 for older participants suggests that they still understood the ACC system fairly well.

Question 20. When using the ACC system, did you ever feel you didn't understand what the system was doing, what was taking place, or how the ACC system might behave?

1	2	3	4	5	6	7
Very Frequently						Very Infrequently

The statistically significant main effect was age, $F(2, 18) = 6.72, p = .007$.

	Mean	
Young	6.63	A
Middle-aged	6.38	A
Older	5.25	B

Means with the same letter are not significantly different from one another.

With regard to comfort when changing lanes to pass (question 22), participants reported feeling significantly more comfortable passing when controlling the vehicle manually as opposed to under ACC. The greatest difference was seen in the responses provided by the young age group, reporting the lowest overall level of comfort with passing in ACC and the highest overall level of comfort passing when under manual control.

Question 22. How comfortable did you feel with your ability to change lanes (to pass other cars) using each of the following modes of operation?

Manual Control	1 Very Uncomfortable	2	3	4	5	6	7 Very Comfortable
ACC	1 Very Uncomfortable	2	3	4	5	6	7 Very Comfortable

The statistically significant main effect was driving mode, $F(1, 18) = 6.682, p = .019$.

	Mean
Manual	6.333
ACC	5.750

A statistically significant interaction was observed for participant age and driving mode, $F(2, 18) = 4.33, p = .029$.

		Mean	Std. Error	95% Confidence Interval	
AGE	MODE			Lower Bound	Upper Bound
Young	Manual	6.750	.300	6.119	7.381
	ACC	5.375	.425	4.482	6.268
Middle-Aged	Manual	6.125	.300	5.494	6.756
	ACC	5.500	.425	4.607	6.393
Older	Manual	6.125	.300	5.494	6.756
	ACC	6.375	.425	5.482	7.268

	Mean			
Young ACC	5.375	A		
Middle-Aged ACC	5.5	A		
Older Manual	6.125		B	
Middle-Aged Manual	6.125		B	
Older ACC	6.375		B	C
Young Manual	6.75			C

Means with the same letter are not significantly different from one another.

The final two questions in which the results were significantly different were for questions 31 and 32. In both instances female participants reported that the ACC system functions and system components were more distracting than did male participants. However, the overall response to either question was still relatively positive.

Question 31. Did you find the ACC system functions distracting (e.g., automatic acceleration and deceleration)?

1	2	3	4	5	6	7
Very Distracting						Not At All Distracting

The statistically significant main effect was gender, $F(1, 18) = 9.48$, $p = .007$.

	Mean
Male	6.67
Female	5.50

Question 32. Did you find the ACC system components distracting (e.g., status lights, control buttons)?

1	2	3	4	5	6	7
Very Distracting						Not At All Distracting

The statistically significant main effect was gender, $F(1, 18) = 6.19$, $p = .02$.

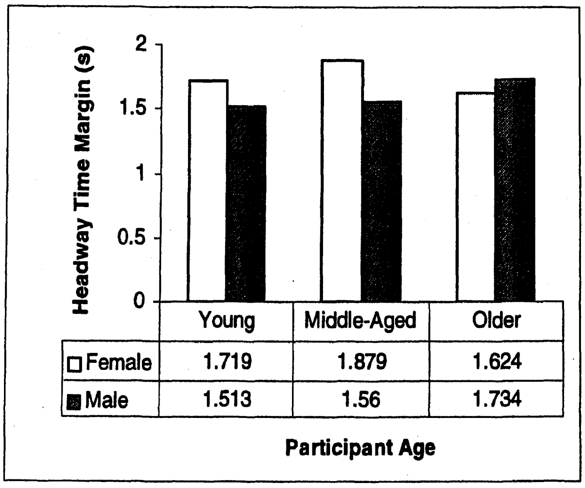
	Mean
Male	6.33
Female	5.00

5.1.4.2 Results from analyses of variance using objective data

Of the independent variables there were no significant differences observed associated with the within-subject variable mode of driving (manual vs. ACC control). Significant differences were observed for the between-subject independent variables of participant gender, participant age, and the interaction of gender and age (collapsed across both modes of driving). With regard to participant gender, significant differences were seen between male and female drivers for the dependent measures of range ($F = 5.8$, $p = 0.027$), headway-time-margin ($F = 7.7, p = 0.013$) and velocity ($F = 6.6, p = 0.019$). Collectively male drivers maintained a 14.4 ft shorter range, a 0.14 s shorter headway-time-margin, and drove nearly 3 ft/s faster than did female drivers under similar conditions.

For the independent variable of participant age, one statistically significant difference was observed. The youngest group of drivers, aged 20 – 30 years, drove significantly faster ($F = 65.8, p = 0.024$) than either the middle-aged or older groups of drivers, where the mean velocities by age group were 100.66, 97.54, and 96.86 ft/s, respectively.

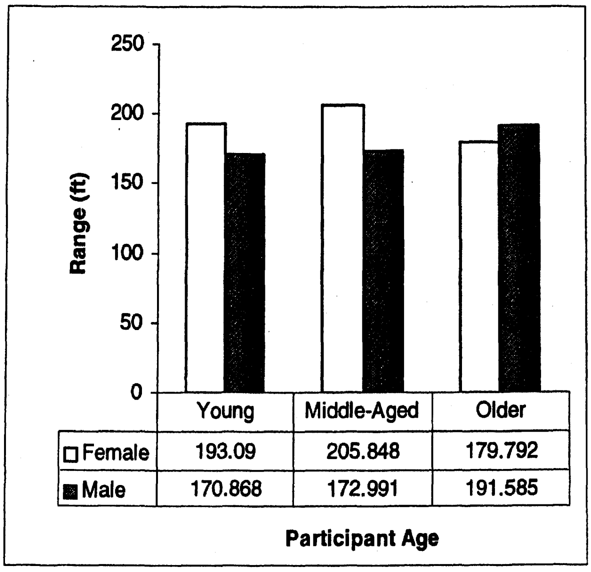
Finally, there were two statistically significant interactions between participant gender and participant age for the dependent measures of headway-time-margin and range (Figure 16 and Figure 17). In both instances, female participants were more conservative than their male counterparts for the young and middle-aged groups. However, male drivers for the older age group were actually more conservative than their female counterparts. The decrease in both headway-time-margin and range for older females, relative to their younger counterparts, is unexpected. One would typically expect to see results for both genders that monotonically increased with increased participant age, such as the case for the results for the male participants.



	Mean			
Young Male	1.513	A		
Middle-Aged Male	1.56	A		
Older Female	1.62	A	B	
Young Female	1.719		B	
Older Male	1.734		B	
Middle-Aged Female	1.879			C

Means with the same letter are not significantly different from one another.

Figure 16. Interaction of participant age and gender for the dependent variable Htm



	Mean			
Young Male	170.9	A		
Middle-Aged Male	173	A		
Older Female	179.8	A		
Older Male	191.6		B	
Young Female	193.1		B	
Middle-Aged Female	205.8			C

Means with the same letter are not significantly different from one another.

***Figure 17.* Interaction of participant age and gender for the dependent variable range**

5.1.4.3 Summary and Discussion of the Statistical Results

Overall, participant impressions of the ACC system they experienced were quite positive. Examination of the summary responses to the questions in Appendix D shows that participants in the study found the system to be convenient, comfortable, easy to use, and even enjoyable to use. Furthermore participants reported that the system was safe to use. While these are summaries, and individual impressions may vary, they are none the less strongly supportive of the belief that lay driver's will accept, appreciate, and find benefit from the implementation ACC with braking.

As observed in both the subjective and objective results, differences in the impressions and system use by groups of drivers exist. In that respect these results are similar to those previously observed in a field operational test of ACC without braking [1]. These group differences, be they subjective or objective, should serve to guide important ACC system design decisions, particularly when specific vehicle models are intended for specific age or gender-based markets.

5.1.4.4 Verification of functional purpose

Figure 18 contains two 2-dimensional histograms. One histogram is for ACC driving and the other is for manual driving on the same route by all 24 drivers.

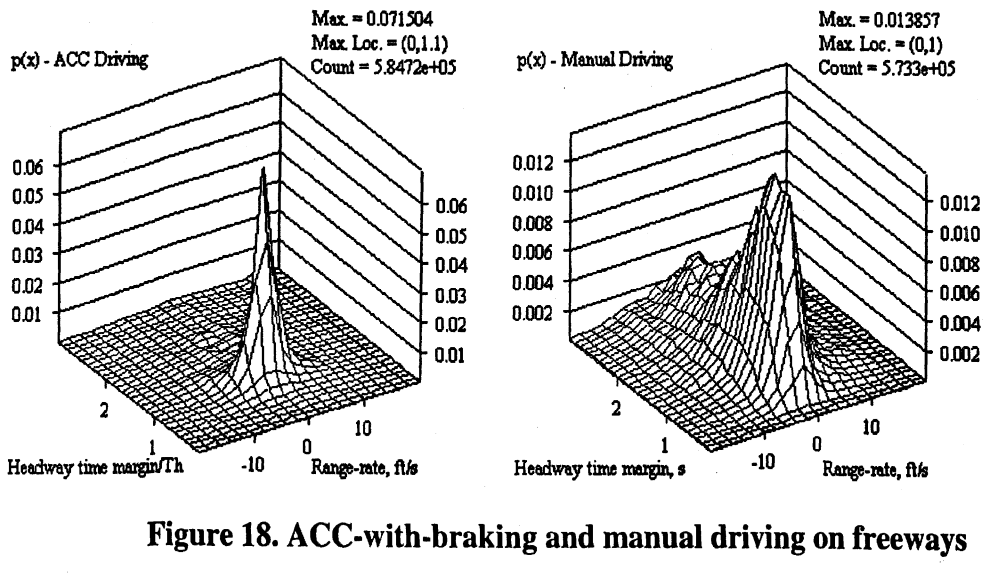


Figure 18. ACC-with-braking and manual driving on freeways

The results for ACC driving show the frequency of various values of normalized headway-time-margin and range-rate. In the plot for ACC driving, the headway-time-margin is normalized by the headway time setting the driver was using. The plot for manual driving employs headway-time-margin directly, but we know that drivers tend to show a most likely value (MLV) in the vicinity of one second of headway time.

Examination of the plot shows that driving with the ACC-with-braking system is much more organized with regard to headway time than is manual driving.

During the FOCAS project, the presentation shown in Figure 18 has taken on a special meaning. It represents prima face evidence (at the highest level of abstraction) that the ACC system works. The figure shows that the ACC-with-braking system satisfies its primary functional purpose. That is, the system controls the position of the car relative to other vehicles such that it achieves the headway time setting chosen by the driver with an extraordinarily high frequency compared to manual driving. (Note that the vertical scale for manual driving is much smaller than the vertical scale for ACC-with-braking. The results indicate a maximum frequency of 0.0138 for manual driving while the maximum frequency for ACC driving is 0.0715—approximately a factor of 5.)

5.1.4.5 Functional Purpose

The following histograms provide results indicating how the ACC-with-braking system performs during freeway driving. Each histogram provides a direct comparison between manual and ACC driving.

Headway-time-margin

Figure 19 shows the form of the histograms for manual and ACC driving. The tabulated information at the bottom of the figure indicates that the means and standard deviations for the results for manual and ACC driving are very nearly equal. However, the MLV are considerably different for the two histograms.

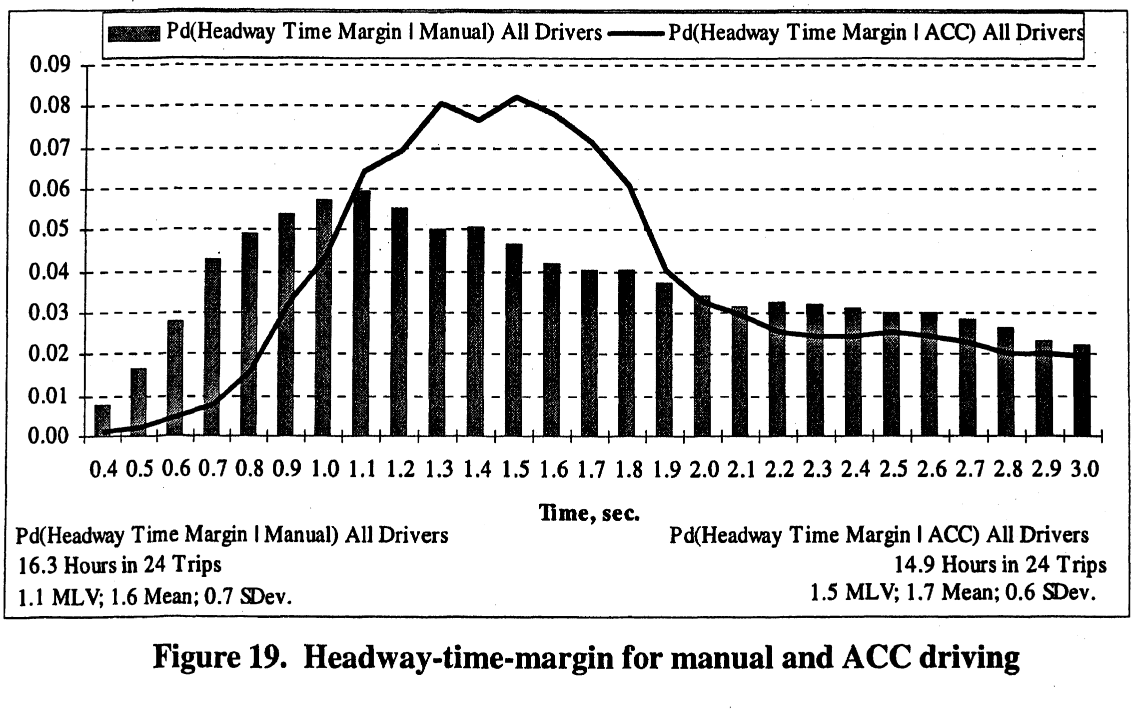


Figure 19. Headway-time-margin for manual and ACC driving

The maximum for manual driving is at 1.1 seconds while the maximum for ACC-with–braking is at 1.5 seconds. These results indicate that drivers provide themselves with more headway time for reacting to changes in the driving situation during ACC driving than they do during manual driving.

Figure 20 presents the cumulative distributions corresponding to the data presented in Figure 19. Examination of these results indicates, for example, that the chance of driving with a headway time of one second or less is approximately 25 percent for manual driving in contrast to approximately 10 percent for ACC driving.

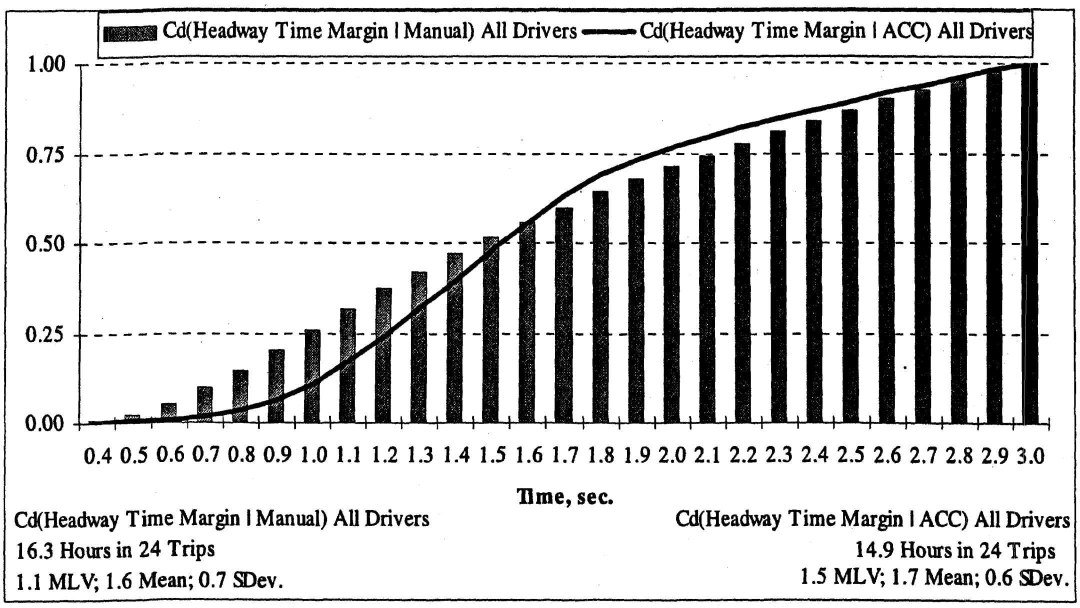


Figure 20. Cumulative distributions for headway-time-margin

Time-to-impact

Figure 21 shows the form of the histograms for time-to-impact covering values less than 18 seconds. Time-to-impact usually has a large value except when the car is closing on a preceding (impeding) vehicle. The formula for time-to-impact is Tti = -R/Rdot for Rdot less than zero. This formula indicates that Tti will be large when Rdot is approximately zero. Closing situations of immediate concern to drivers usually involve Tti values less than 18 seconds with 10 seconds appearing to be a threshold below which many drivers might be expected to apply braking.

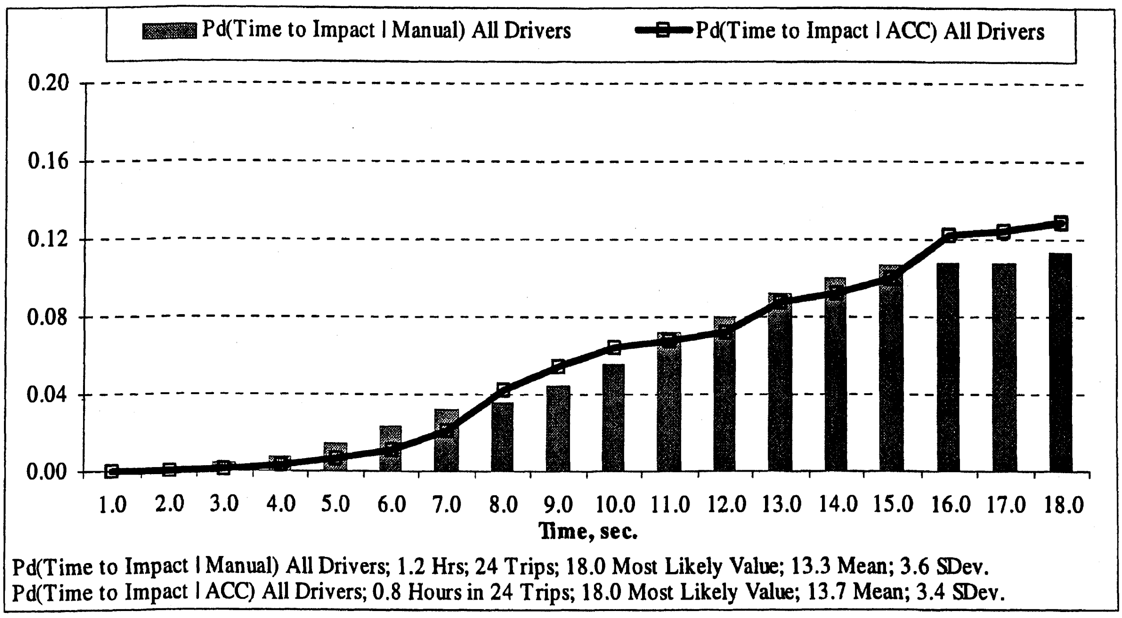


Figure 21. Time-to-impact for manual and ACC driving

The results in Figure 21 show that the time-to-impact in closing situations in ACC driving is very similar to that observed in manual driving. With regard to time-to-impact, the ACC system created for the FOCAS project performs in a manner that is similar to the way people drive manually.

Figure 22 shows the cumulative distributions corresponding to the data presented in Figure 21. (We often employ cumulative distributions to present results for time-to-impact.) Examination of Figure 22 indicates that Tti seldom gets to less than 5 seconds in either ACC or manual driving situations.

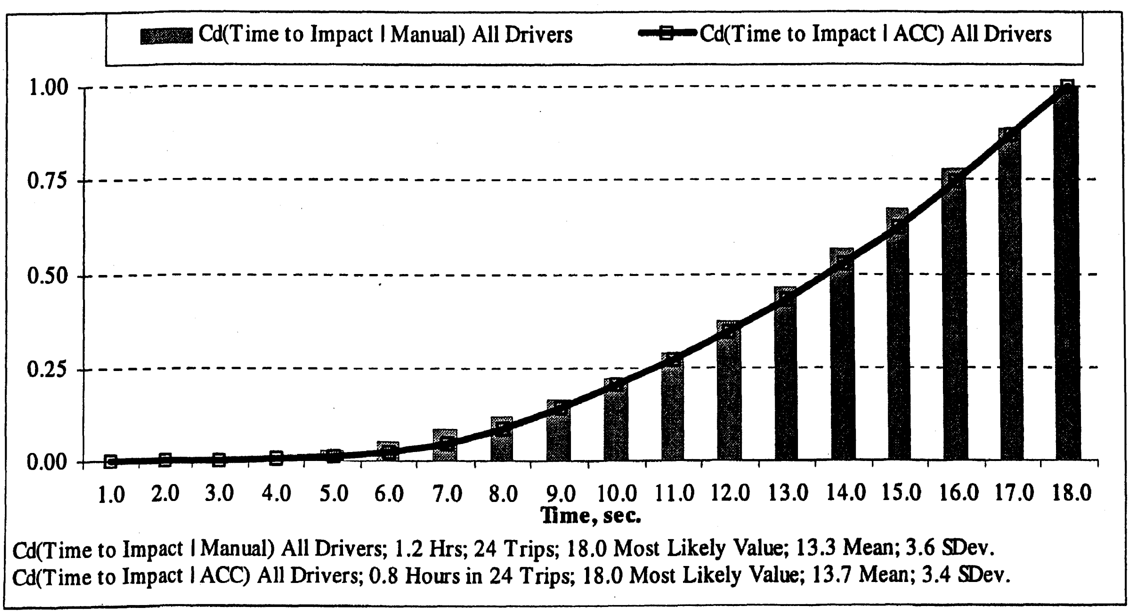


Figure 22. Cumulative distributions for time-to-impact

Throttle control

Figure 23 shows histograms showing the frequencies for various levels of throttle setting for ACC and manual driving on freeways.

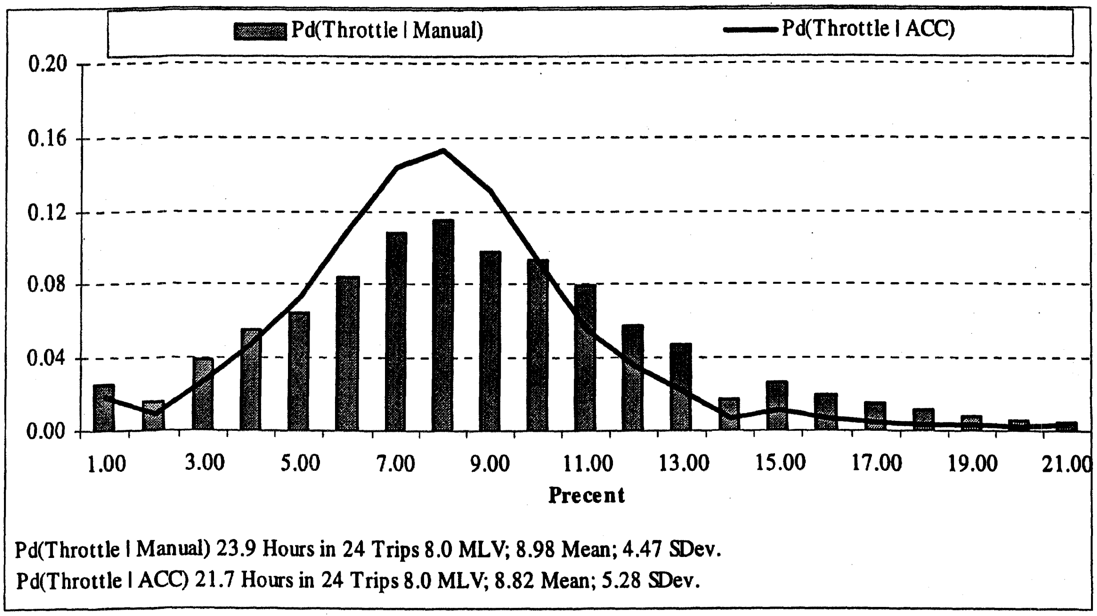


Figure 23. Throttle control for manual and ACC driving

Both histograms show a most-likely value at 8 percent of full throttle (full accelerator pedal position). This is the level of steady state throttle setting that is required to maintain a speed of about 100 ft/s on level roadway in the FOCAS vehicle. Note that there is a slight tendency for higher throttle settings in manual as compared to ACC driving. This could mean that ACC driving might be more fuel efficient than manual driving. However the effect does not appear to be large, and direct measurement of fuel economy in the two modes would be needed to quantify the difference. Nevertheless, the ACC system could be expected to have a fuel economy advantage.

Figure 24 shows the cumulative distributions corresponding to the data presented in Figure 23. Examination of Figure 24 indicates that about 50 percent of the manual throttle settings are less than 8 percent (approximately the level of throttle setting corresponding to that needed to maintain highway speed). In comparison, for ACC driving, the percentage of values less than 8 percent throttle is approximately 60 percent. In this sense ACC driving is more speed consistent than is manual driving.

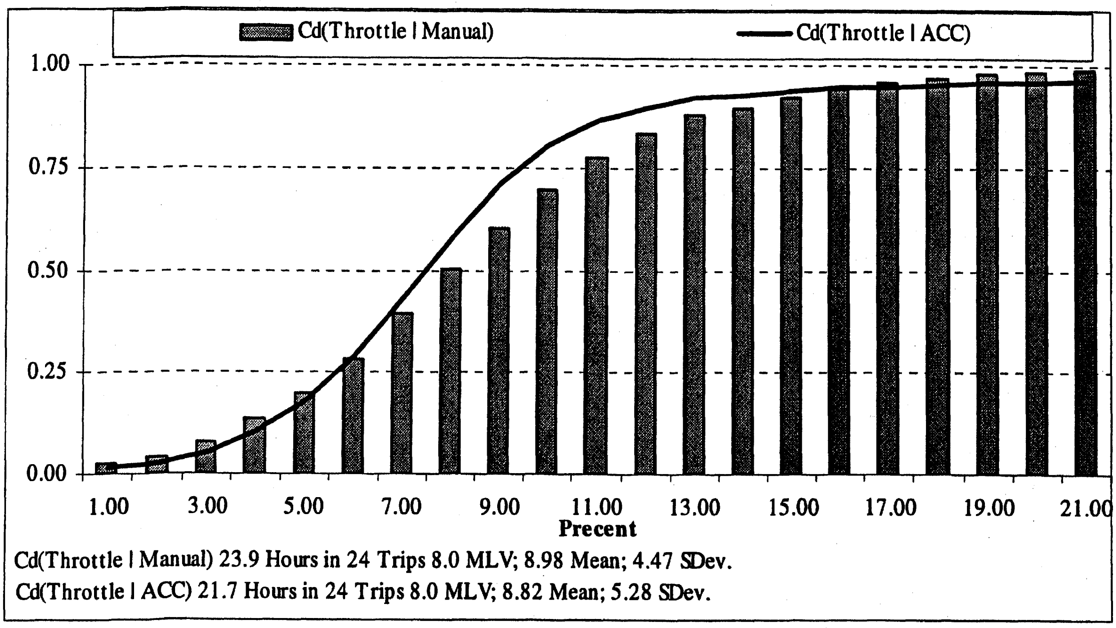


Figure 24. Cumulative distributions for throttle control

5.1.4.6 Results Concerning Driver Behavior in FOCAS

Manual driving

The results concerning driver behavior are presented using small multiples techniques for data presentation that were employed in the ICC FOT [1]. This technique involves the driver's tendencies with regard to relative speed of travel and range to the preceding vehicle. Figure 25 consists of 24 small plots (miniatures) showing the tendencies measured for each driver in manual driving. At the bottom of the figure, there is a legend showing how the miniatures are constructed. The horizontal axis displays the amount of fast or slow driving while the vertical axis shows the amount of close or far driving performed by the driver. For example, the driver labeled 21-E in Figure 25 stands out from the others because of the amount of shaded area going in the close direction. The number 21 is the code used to identify this particular driver. The E means that this driver has been classified with the name extremist per the ICC FOT conventions. This means that not only does this driver travel close but also has characteristics indicating another type of extreme behavior. In this case, driver 21 also appears to travel relatively far away from other drivers while traveling fast— a characteristic associated with the planner (P) style in the ICC FOT terminology. Drivers with more than one extreme tendency are called extremists. Figure 25 (in the top row) indicates five extremists among the 24 lay-drivers that participated in the FOCAS study. However, driver 21 is the only extremist that had a close driving tendency. None of the other extremists had a close tendency.

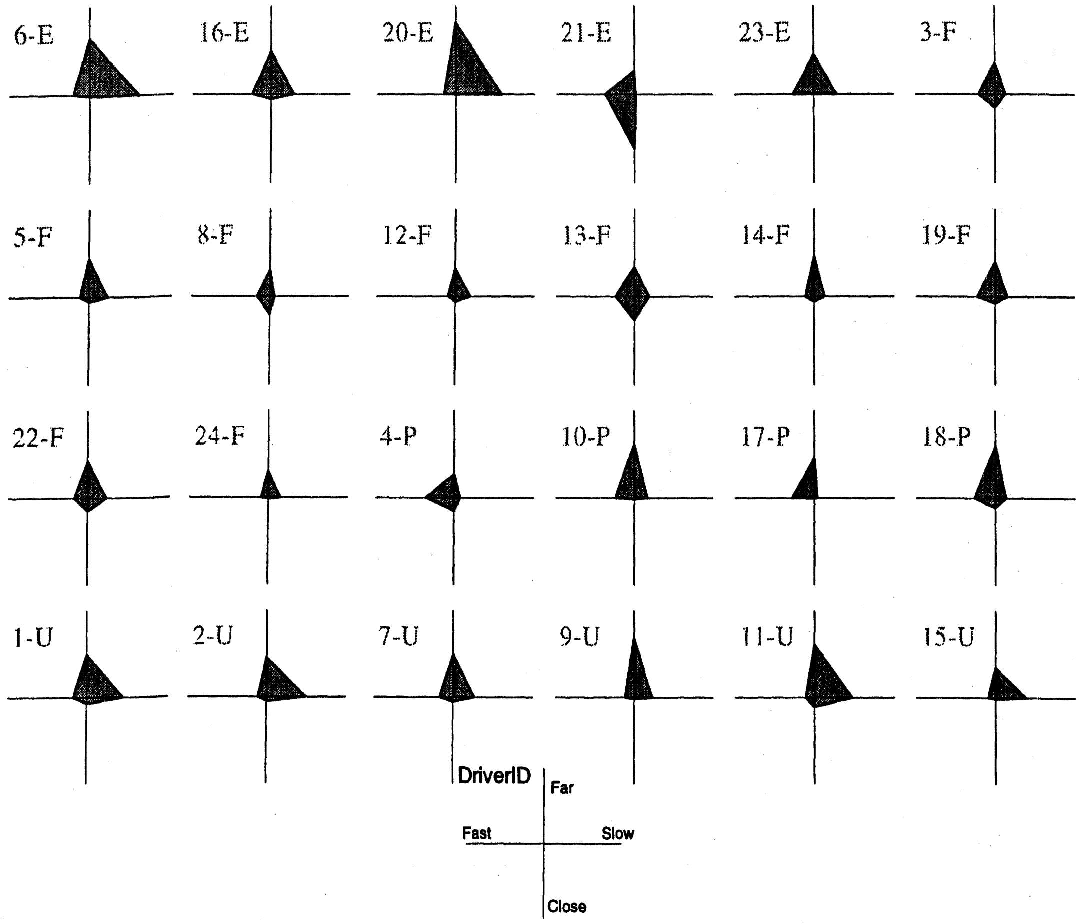


Figure 25. FOCAS manual driving styles

Next, there are nine followers indicated by an F in Figure 25. These drivers tend to travel at the same speed as adjacent traffic at typical headway ranges.

There were four planners (P). This type of driver has a remarkable ability to avoid coming close to preceding vehicles although they tend to travel at relatively high speeds. They plan in a manner that allows them to steer around vehicles that would be impediments to them.

Finally, there were six ultraconservatives (U). These drivers tend to drive slower than other drivers in the traffic stream. Since they are traveling slowly, they seldom get close to other vehicles. Other vehicles cut in front of them but the range increases to large values until somebody else takes the gap. Ultraconservatives are distinguished by large far and slow tendencies.

ACC-with-braking driving

Figure 26 shows the corresponding set of results for driving behavior when the ACC system is operating. This figure has the same order of driver numbers as that used in

Figure 25 (the previous figure). However, the driving styles are modified due to the performance of the ACC system. In ACC, the drivers select both their maximum speed value and their desired headway time. The results indicate that with the ACC in operation there were 13 followers, 5 planners, and 6 ultraconservatives. There were no extremists when the ACC was in operation.

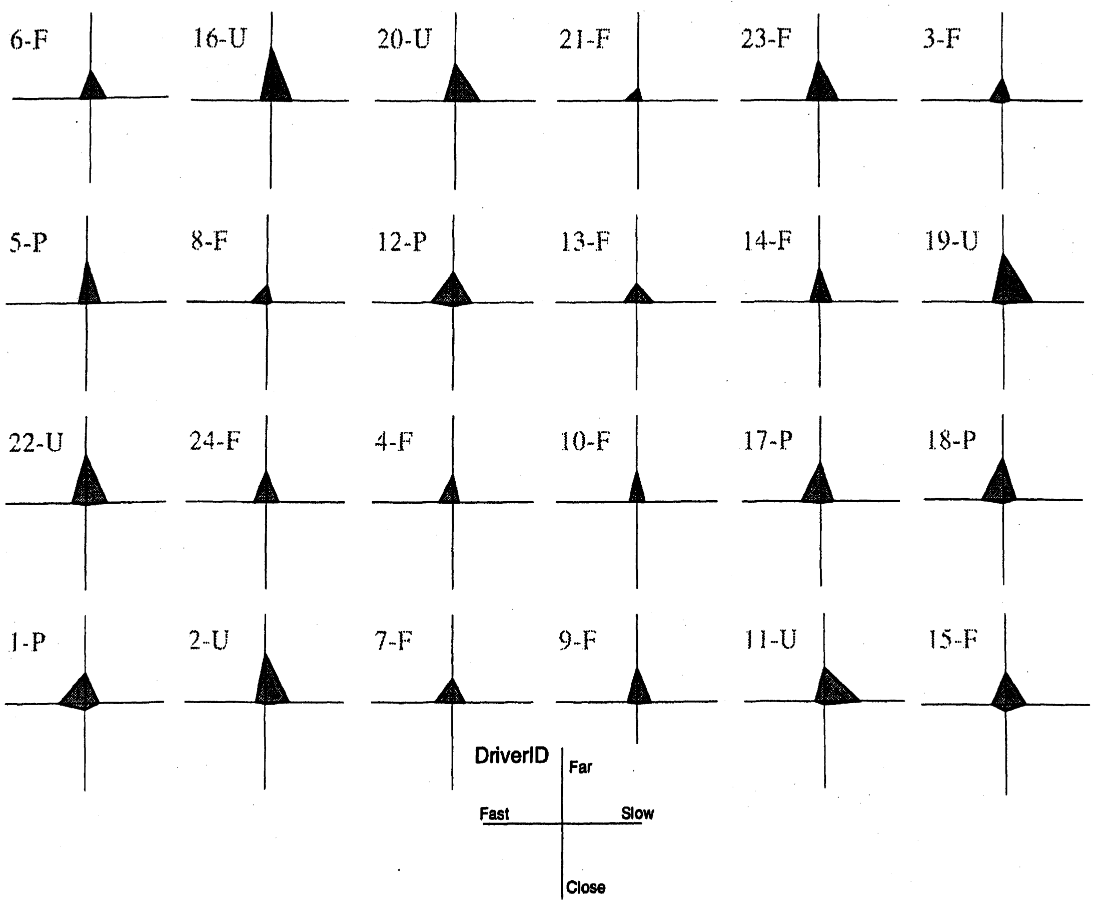


Figure 26. FOCAS ACC driving styles

The size of the area shown for some of the drivers is quite small as shown in Figure 26. For example, the area for driver 21 is much larger in Figure 25 for manual driving than it is for ACC driving in Figure 26. This indicates that use of the ACC system greatly modified the driving style of this driver. A very small area is associated with the follower style. Driver 21's style became very consistent with regard to speed and headway as indicated by the small area shown in Figure 26. Inspection of Figure 25 and Figure 26 indicates that the ACC style of many of the drivers was much more consistent than their manual driving style.

5.1.4.7 Comparisons between FOCAS and ICC FOT results

The participants in the FOCAS study were accompanied by a researcher and drove only on a specified route during mid-morning and mid-afternoon periods during which traffic was light. In contrast, participants in the ICC FOT drove unaccompanied whenever, wherever, and however they chose to drive. The differences shown in the following results are largely due to differences in the constraints imposed in the two studies.

Time-to-impact

Figure 27 shows comparisons for both ACC and manual driving. In the two ACC cases, the cumulative distributions for time-to-impact are very much alike. This is to be expected since the control algorithms were much the same with regard to the objective function for controlling headway. (The main difference was that the maximum deceleration authority in the ICC FOT was 0.06 g while the maximum deceleration authority in FOCAS was 0.22 g.)

The time-to-impact results are noticeably different for manual driving, however. In FOCAS, the frequency of small values (below 10 seconds) was smaller than it was in the ICC FOT. The presence of the researcher in the car appears to have made the drivers more conservative. Also, the freeway-only environment and mid-day traffic conditions of the FOCAS experiment involved fewer situations involving cut-in and near encounters.

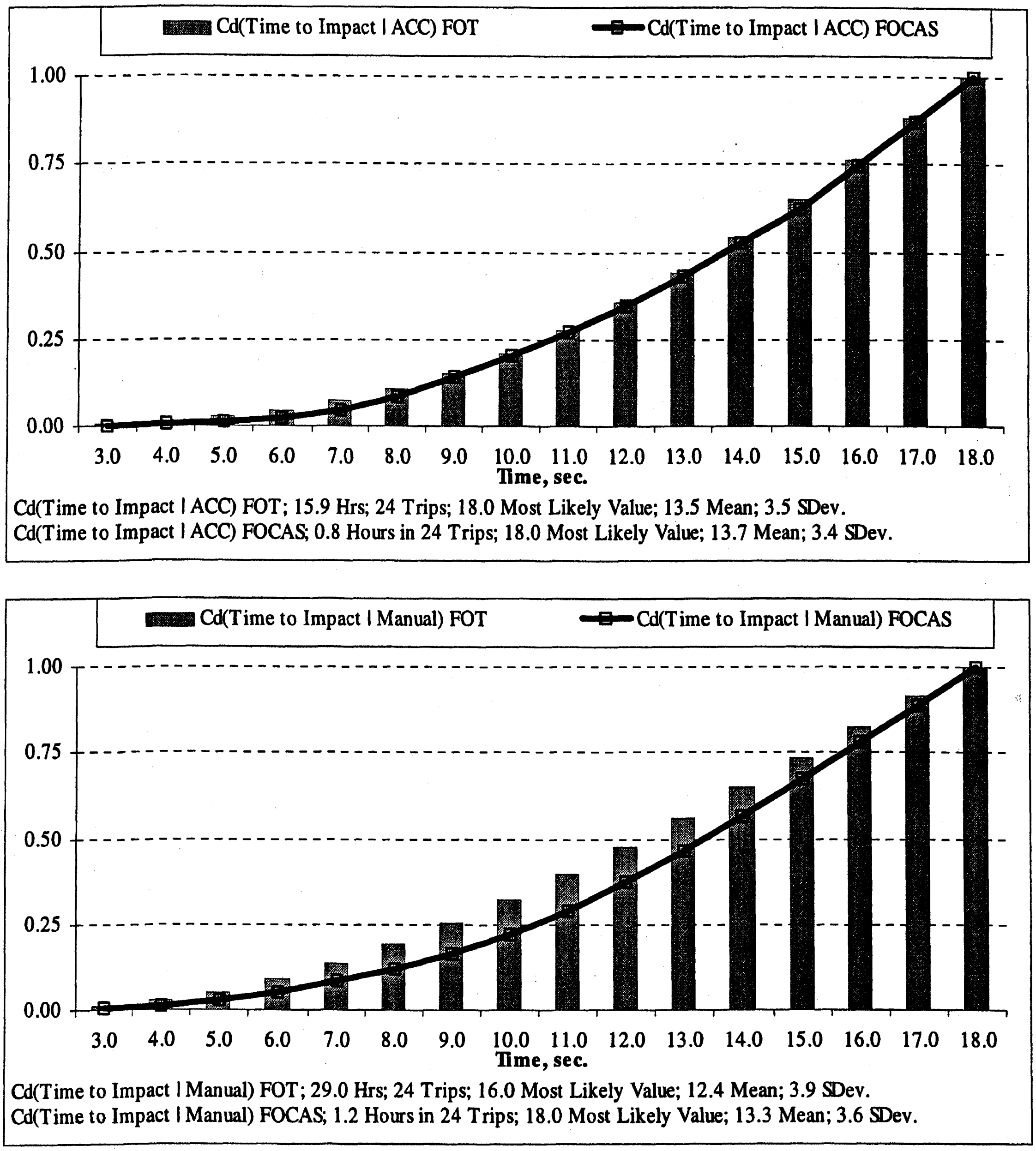
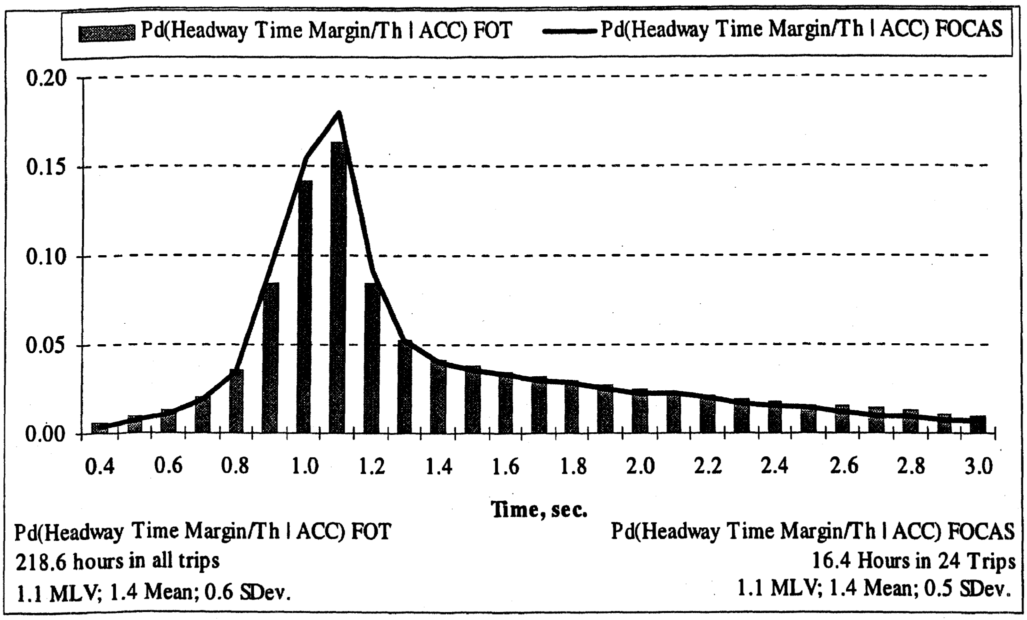


Figure 27. Time-to-impact in FOCAS and ICC FOT driving

Headway-time-margin

Figure 28 shows comparisons for both ACC and manual driving for headway-time-margin. As with time-to-impact (Figure 27), the cumulative distributions for ACC driving are very much alike. This is to be expected since the control algorithms were much the same with regard to desired headway time.



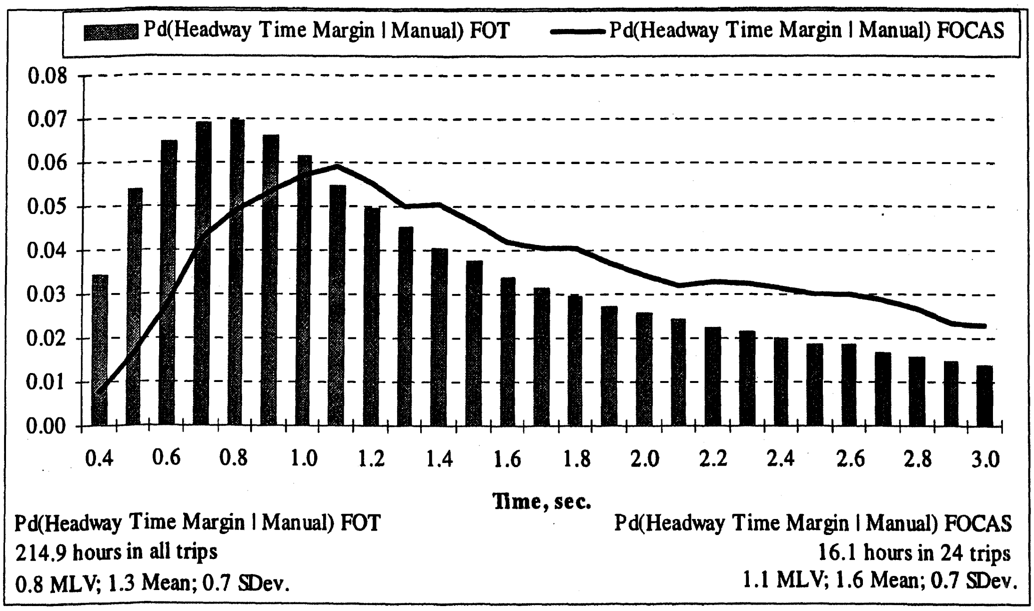
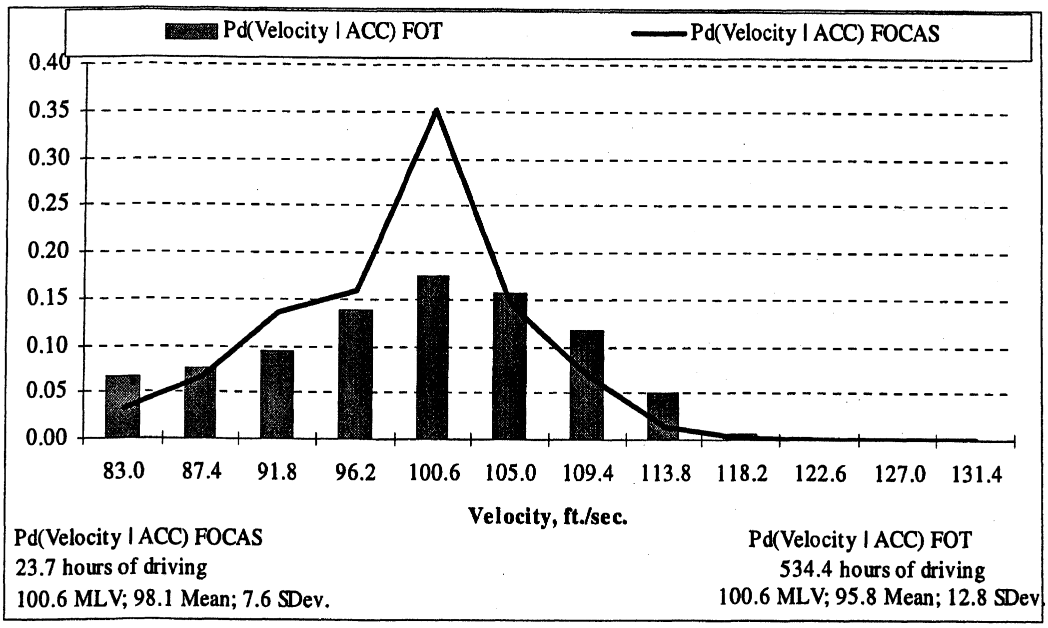


Figure 28. Headway-time-margin in FOCAS and ICC FOT driving

The results for headway-time-margin are noticeably different for manual driving. In FOCAS, the most frequent value of headway time was approximately 1.1 seconds. In the ICC FOT, it was 0.8 seconds. Again, the presence of the researcher in the car and differences in traffic density appear to have made the drivers more conservative.

Velocity

Figure 29 shows velocity-histograms for both ACC and manual driving in both the FOCAS and ICC FOT studies. With regard to velocity, the results for both manual driving and ACC driving are noticeably different.



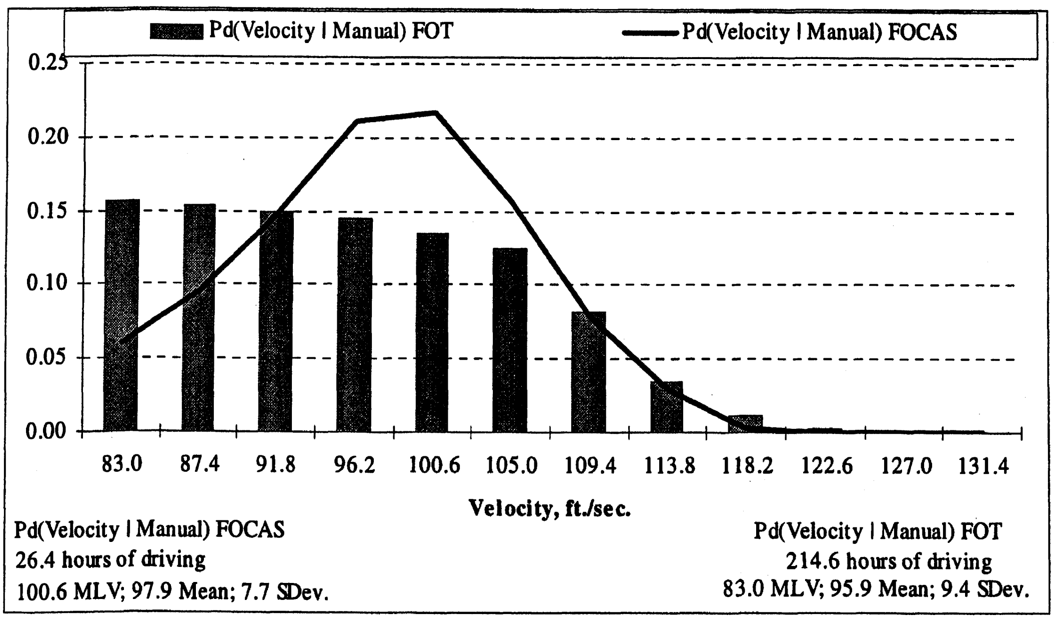


Figure 29. Velocity in FOCAS and ICC FOT driving

In the FOCUS study, the ACC system is much more responsive than it was in the ICC FOT. We believe that this partially accounts for the relatively high frequency at 100.6 ft/s in the FOCAS study. Also, the freeways used in the FOCAS study appear to have traffic that travels mainly in the vicinity of 100 ft/s.

Perhaps the differences in the driving environment between the FOCAS study and the ICC FOT study are emphasized in the manual driving results. Figure 29 shows that the manual driving results for speeds above 55 mph (80 ft/s) form a relatively flat distribution with a most frequent value at 83 ft/s. The FOCAS results in the same plot show a most frequent value at 100.6 ft/s. The results show that the spread of likely velocities was much narrower in the FOCAS study than it was in the ICC FOT study.

5.1.4.8 Driving Styles FOCAS versus ICC FOT

Figure 30 is a bar chart showing the frequencies of manual driving styles observed in the FOCAS and ICC FOT programs. The figure includes a driving style called hunter/tailgater that was not previously mentioned when discussing Figure 25 entitled "FOCAS manual driving styles." Hunter/tailgaters (H) is the name given to drivers that have a tendency to drive close and fast. In the FOCAS study, as indicated in Figure 25, an extremist (driver 21) tended to drive fast as well as both close and far. This was the only one of the 24 FOCAS drivers that displayed a tendency to drive extremely close. We believe that, because the participants were accompanied by a researcher, they did not tend to tailgate. Apparently, drivers are hesitant to tailgate if they are being observed by an onboard researcher.

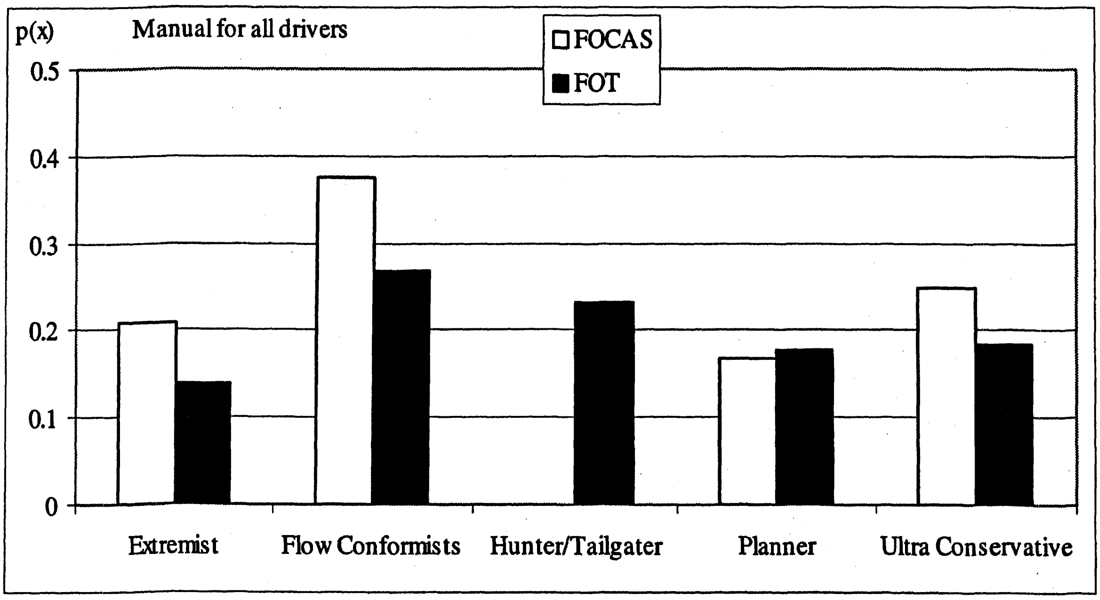


Figure 30. Manual driving styles

Otherwise, the manual driving styles for FOCAS appear to be similar to those observed in the ICC FOT with a few more flow conformists, extremists, and ultra-conservatives to make up for the lack of hunter/tailgaters.

Figure 31 presents results comparing ACC driving. As indicated, the ACC system eliminated tailgating in both studies. Furthermore, the ACC-with-braking system used in the FOCAS study eliminated the extremist cases. As shown here and as discussed previously, the FOCAS drivers became either flow conformists, planners, or ultraconservatives. If the driver adjusts the set speed to about the speed of traffic and chooses a headway time setting in the range of approximately 1.2 to 1.8 seconds, the driving style will tend to be classified as flow conformist. If the driver tends to pick a higher set speed but is good at planning a path for steering around slower moving vehicles, the result will be classified as a planner. One can always be ultra-conservative by choosing a set speed that is less than the speed of adjacent traffic. In summary, the ACC-with-braking system tends to constrain driving to a flow conformist style unless the driver chooses a set speed that is significantly faster or slower than that of the prevailing traffic stream.

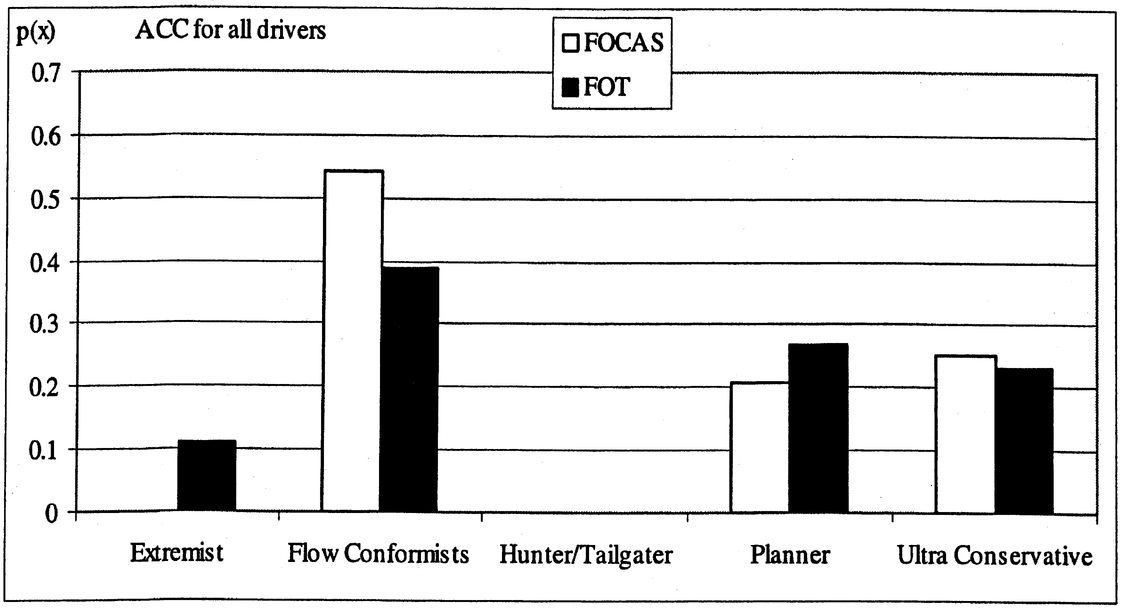


Figure 31. ACC driving styles

5.1.4.9 Braking results from FOCAS

In the FOCAS study, drivers applied the brakes to control speed and distance in manual driving or to intervene on the ACC-with-braking system. In addition, the ACC system used the brakes when it determined that braking is needed to return the vehicle to a state of travel where throttle modulation will be sufficient to maintain the desired headway. In the results that follow, there are plots showing manual braking, ACC braking, and manual braking interventions on ACC operation. The deceleration authority of the ACC-with-braking system was 0.22 g. This was the maximum level of deceleration that the ACC system will employ. If higher deceleration is desired, the driver must apply the brakes manually.

When does braking occur?

Table 5 provides a classification indicating reasons for manual intervention on ACC operation. These results are based upon notes recorded by the researcher riding in the

ACC-equipped vehicle. In addition, the researcher reviewed videotapes to confirm and supplement the information recorded in the notes.

Table 5. ACC Brake intervention reasons for FOCAS

Reason	Number	Crash/Discretionary
Exit ramp	14	Discretionary
Don't know ?	5	Discretionary
Cut in	3	Crash Avoidance
Police	3	Discretionary
Traffic slowdown	10	Crash Avoidance
Traffic merging	5	Crash Avoidance
Construction zone	3	Crash Avoidance
Slow down for a crash	1	Crash Avoidance
Not slowing for a curve	1	Discretionary
Total	45	22 Crash Avoidance

As indicated in the table, many of the interventions were deemed to be of a discretionary nature as contrasted to a necessary or crash avoidance nature. Approximately half of the interventions were classified as crash avoidance. This trend is believed to apply to manual driving also. The cases of ACC braking are all situations in which the system was striving to get to the headway time set by the driver. (i.e., there are no purely discretionary cases for the ACC system.)

In the FOCAS driving, there were 155 cases of manual braking on the freeway, 164 cases of automatic (ACC) braking, and 45 cases where the driver intervened on the operation of the ACC system. Figure 32 presents cumulative distributions for headway-time-margin (Htm) for manual driving, ACC driving, and interventions on ACC driving. These plots are based upon range and velocity measurements at the time of brake application. The plot in the lower part of the figure shows results based upon the crash avoidance type of interventions only.

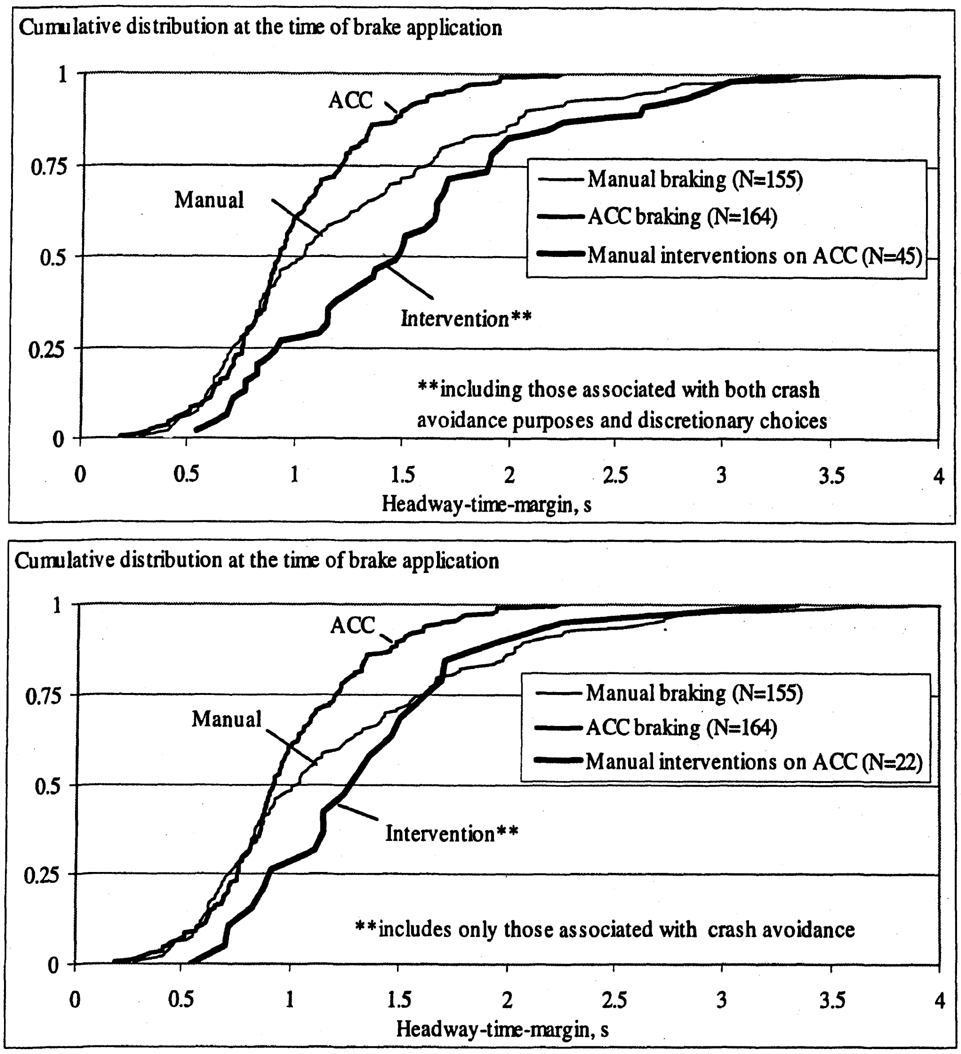


Figure 32. Headway-time-margin (Htm) at time of brake application

Examination of the upper and lower plots in Figure 32 indicates that the removal of the discretionary ACC interventions does not have much influence on the distribution, especially at the lower (critical) values of headway-time-margin. This illustrates the difficulty associated with examining braking data. Drivers usually brake before they have reached a critical situation. They seem to anticipate how the driving situation will develop and decide to brake before the situation becomes stressful. This means that discretionary and crash avoidance braking events often involve the same levels of deceleration. Nevertheless, we can examine the tails of the distributions where headway-time-margin becomes small.

The distributions for manual and ACC braking in Figure 32 are nearly the same at the lower values of Htm up to about 0.8 seconds. This data supports the idea that the braking of the ACC system is similar to that of manual braking when headway-time-margin is small.

The data also show that manual driving is characterized by more frequent braking at higher levels of Htm. This to be expected since manual driving includes many discretionary braking events that are not part of ACC driving.

It is interesting to observe that there is almost no ACC braking at Htm values exceeding 2.0 seconds. Possible reasons for this are that drivers seldom use headway settings above 2 seconds and the chance of getting into situations that require ACC braking is less if the headway setting is high.

Figure 33 contains cumulative distributions for range-rate (Rdot) and time-to-collision (Ttc) at the time of brake application. Examination of the plots in this figure shows that ACC and manual braking are much alike up to Rdot values equal to approximately –8 ft/sec. In terms of time-to-collision (Ttc = -R/Rdot) this translates into levels of Ttc less than approximately 8 seconds.

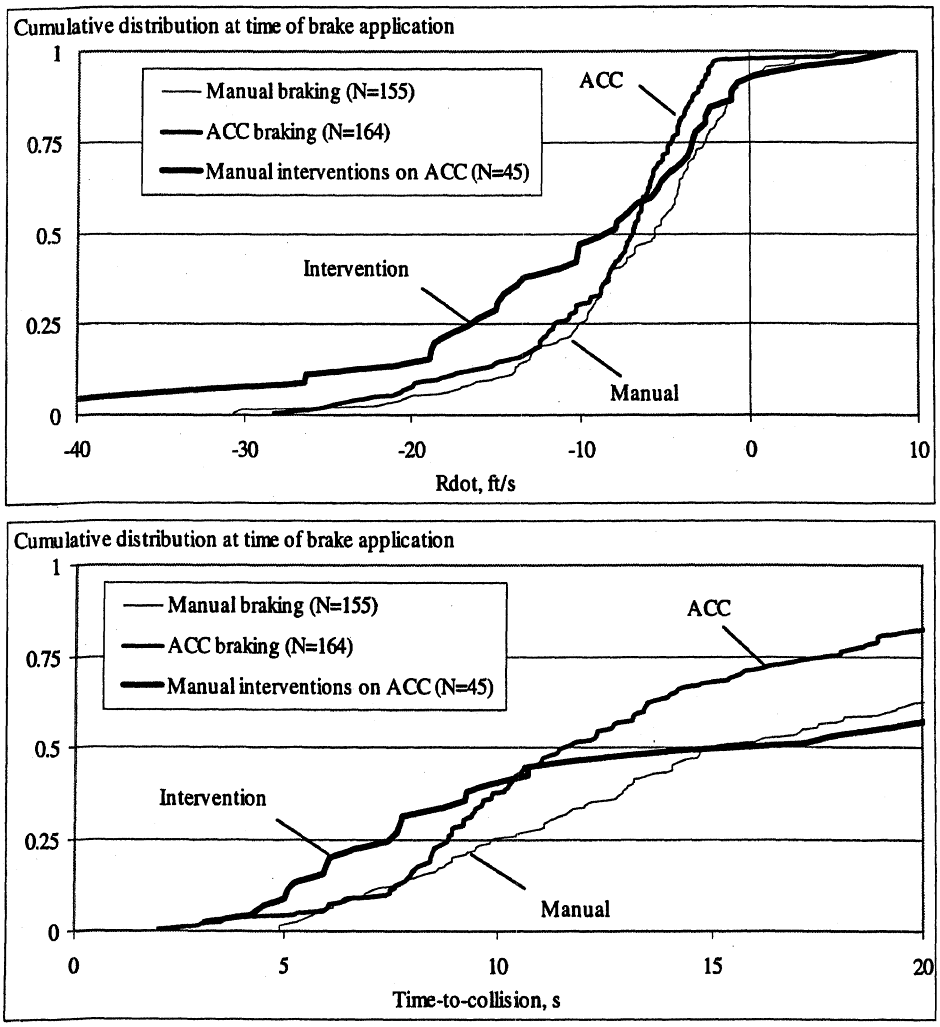


Figure 33. Range-rate (Rdot) and time-to-collision (Ttc) at time of brake application

The results for interventions in Figure 33 indicate that interventions on ACC driving frequently involve large negative values of Rdot and small values of time-to-collision. This is to be expected since the driver is the supervisor of the ACC system. The driver is expected to take over in situations that the ACC system does not handle to the driver's satisfaction. Often this is when the driver becomes anxious and feels stress.

With regard to comparing ACC to manual driving, the ACC system's braking rules do not command braking when Rdot is positive and the vehicles are separating. The results shown in Figure 33 indicate that braking is almost never initiated when Rdot is positive in ACC and manual driving (and for interventions for that matter).

Figure 34 presents cumulative distributions for the deceleration of the preceding vehicle (Vpdot) and the velocity of the subject vehicle at the time of brake application. The results shown for manual, ACC, and intervention braking indicate that the preceding vehicle is decelerating in approximately 75 percent of the cases. In approximately 50 percent of these cases (that is the ones below -0.05 g), the driver of the preceding vehicle would have been applying the brake pedal and the brake lights would have been activated.

At deceleration levels of Vpdot less than -0.1 g, the manual and ACC distributions are alike. However, as is to be expected, the frequency of intervention braking is larger for deceleration levels in the neighborhood of -0.2 g than it is for ACC braking. In general (although infrequent), the frequency of ACC braking is less than that observed in manual driving at deceleration levels below about -0.1 g.

The results for the velocity of the subject vehicle (in Figure 34) show that braking tends to occur at lower speeds in manual driving than it does in ACC or intervention situations. For example, the 50th percentile for the initiation of ACC braking is at approximately 100 ft/s, while approximately 80 percent of the manual braking cases occur at speeds less than 100 ft/s. This might be caused by the greater likelihood of driving at lower speeds during manual driving. Nevertheless, this difference represents an important factor in distinguishing manual from ACC braking.

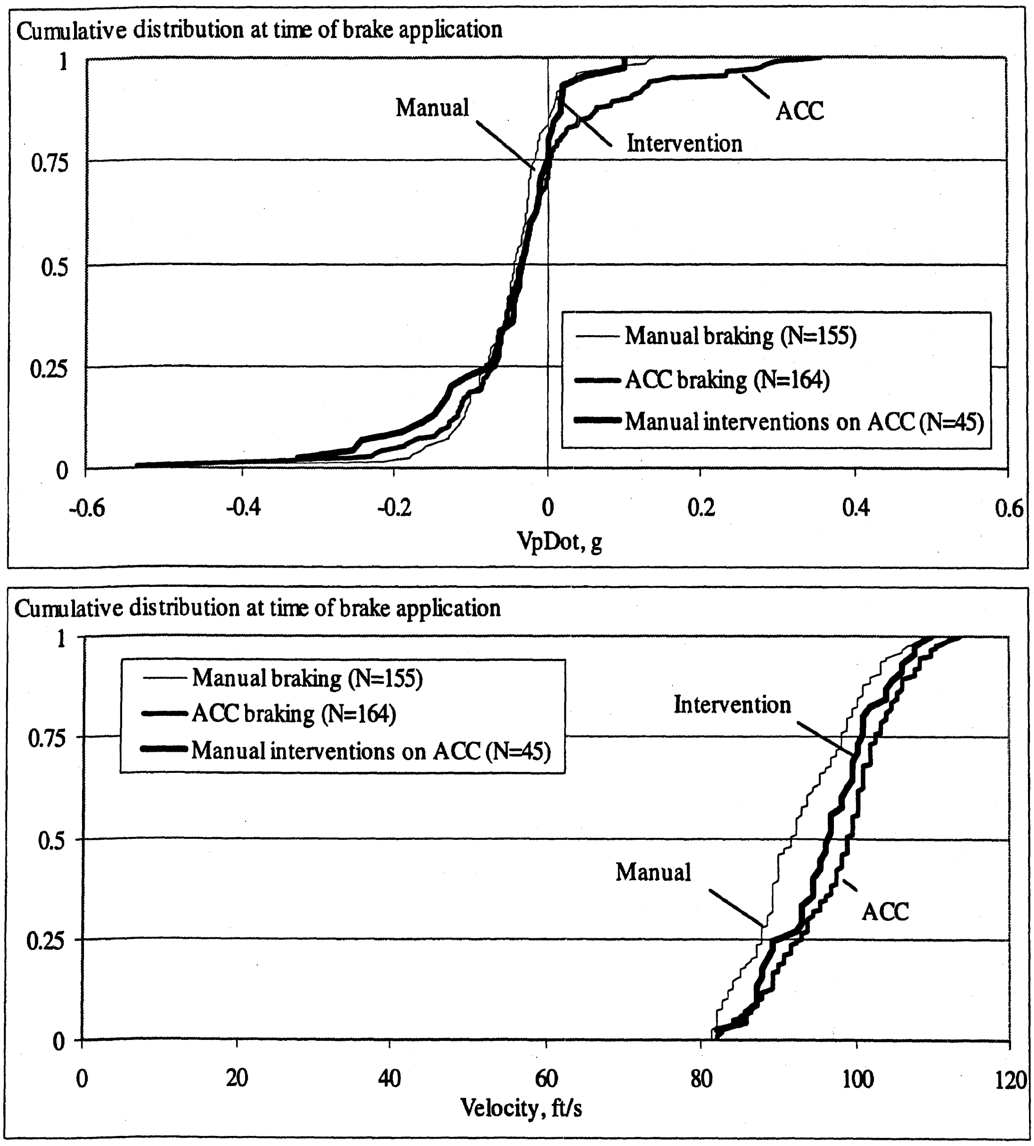


Figure 34. Deceleration of the preceding vehicle (VpDot) and velocity of the subject vehicle at the time of brake application

Figure 35 provides further information concerning braking intervention on ACC driving. This figure compares intervention results taken from the ICC FOT database with the intervention results obtained in FOCAS. The figure shows that, although the deceleration authority was only 0.07 g in the ICC FOT, the results from the two programs are quite similar up to approximately 1 second of headway-time-margin. Approximately, 55 percent of the brake interventions are at headway-time-margins less than 1.0 seconds. The results from the ICC FOT are used in the vigilance study presented in section 5.5 in order to have more cases to work with. In addition, the cases taken from the ICC FOT database are all "necessary" (crash avoidance cases). This accounts for why the distributions start to diverge above 1.0 seconds.

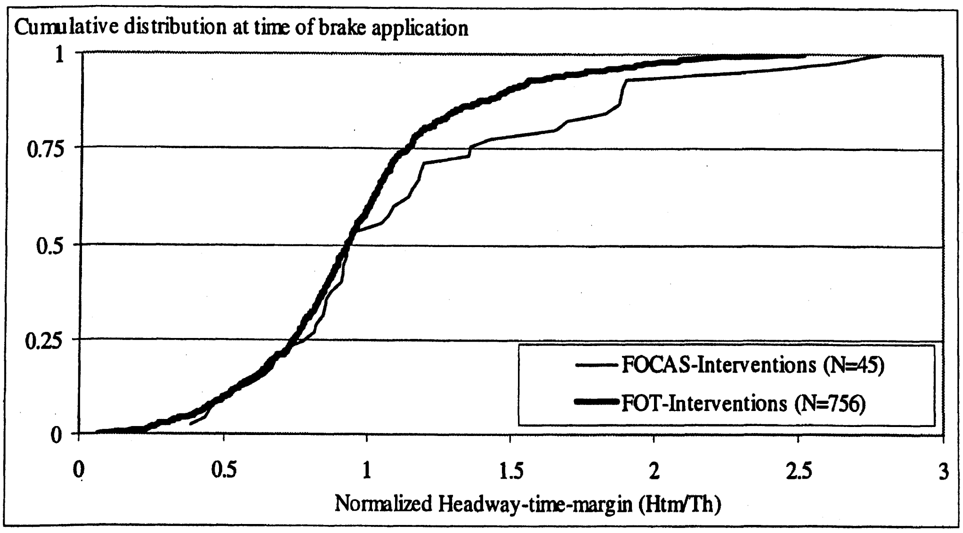


Figure 35. Cumulative distributions of normalized Htm for FOCAS and FOT ACC brake interventions

What is the control objective during braking?

Figure 36 presents results comparing the headway-time-margin (Htm) at the time of brake release (the top plot) with Htm at the time of brake application (the lower plot). Interestingly there is not much difference. The explanation of this involves an understanding of driver behavior. Based upon our observations and speculations, we believe that drivers become very anxious when headway-time-margins fall below a certain threshold (which may vary from driver to driver). In section 5.2 in the discussion concerning braking latency and wait time, we present evidence supporting the following proposition. Drivers hesitate to give up headway-time-margin below their tolerance threshold. In this sense, braking often leads to a headway-time-margin that is nearly the same as that which prevailed when the brakes were applied. That is, with the preceding vehicle decelerating in most of the more demanding cases, the ACC driver applies the brake and maintains a deceleration that more or less nulls the Rdot condition, so as to preserve the tolerance threshold value of headway-time-margin, and then releases. This is especially true at the moment of brake release for manual driving. The ACC system emulates manual behavior to a limited extent.

Figure 37 displays results for time-to-collision, velocity, and Vpdot at the time of brake release. These results indicate that there are differences between the state of the driving situation depending upon whether the braking action is manual, ACC, or intervention. At the time of brake release, the preceding vehicle is usually accelerating (Vpdot > 0). Zero acceleration is associated with approximately the 25th percentile for ACC driving and slightly higher frequency for manual driving. Since the driver anticipates how the driving situation will develop, the measurements at the time of brake release may not indicate all of the information the driver is using to decide to release the brake. Nevertheless, these measurements provide some insight into what the driver expects to achieve by braking.

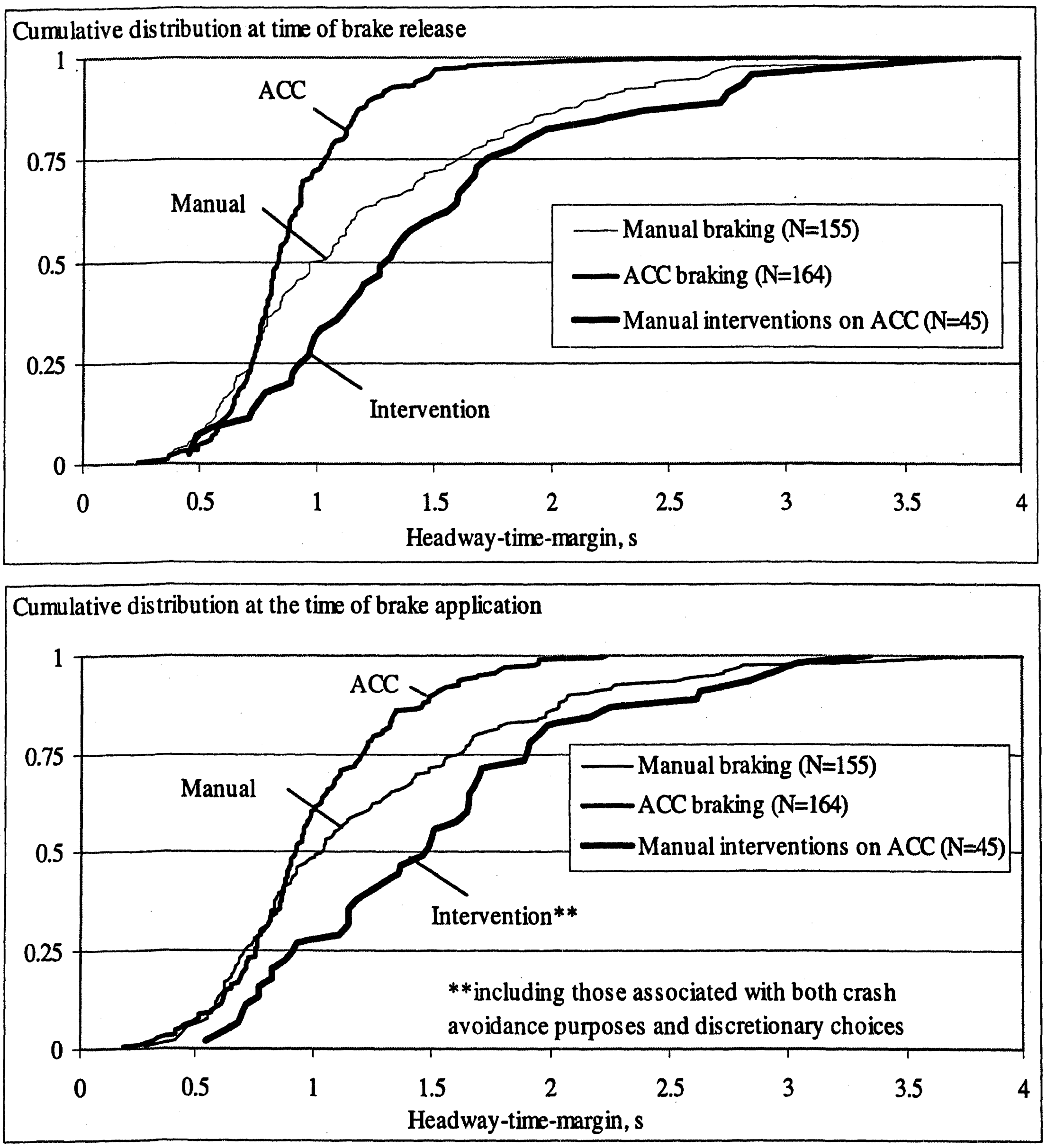


Figure 36. Headway-time-margin at the time of brake release and at the time of brake application

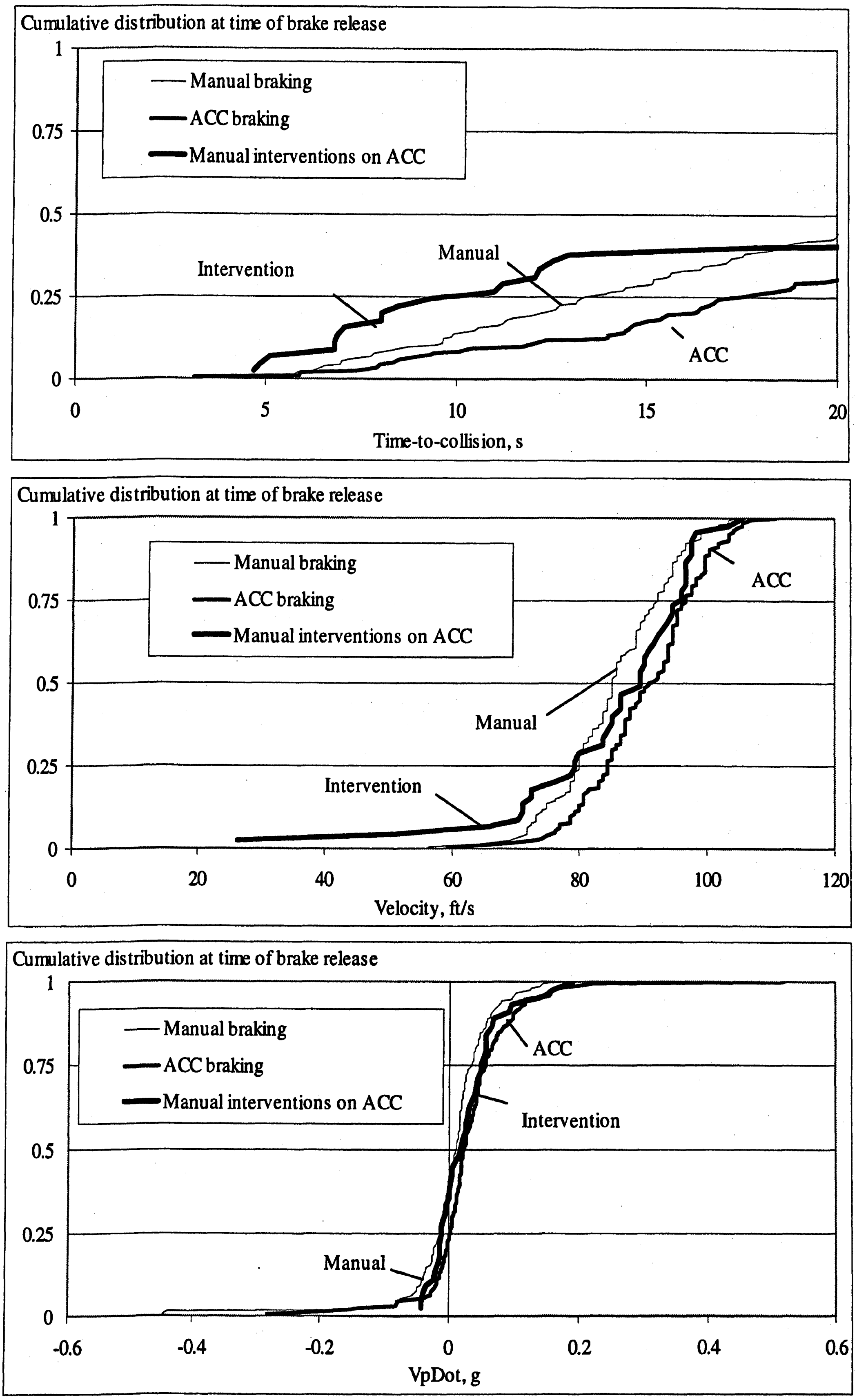


Figure 37. Results for Ttc, velocity, and Vpdot at brake release

Figure 38 pertains to range-rate (Rdot) at the time of brake release. Although negative values of range-rate mean that the range is getting smaller, range-rate is often negative when the brake is released. Drivers are closing towards the preceding vehicle in 75 percent of the braking situations for manual, ACC, or intervention braking. This may appear to be surprising. However, since the ACC braking has this same trend, it appears that the driving situation has been resolved to the point where braking is no longer required to achieve a suitable headway time.

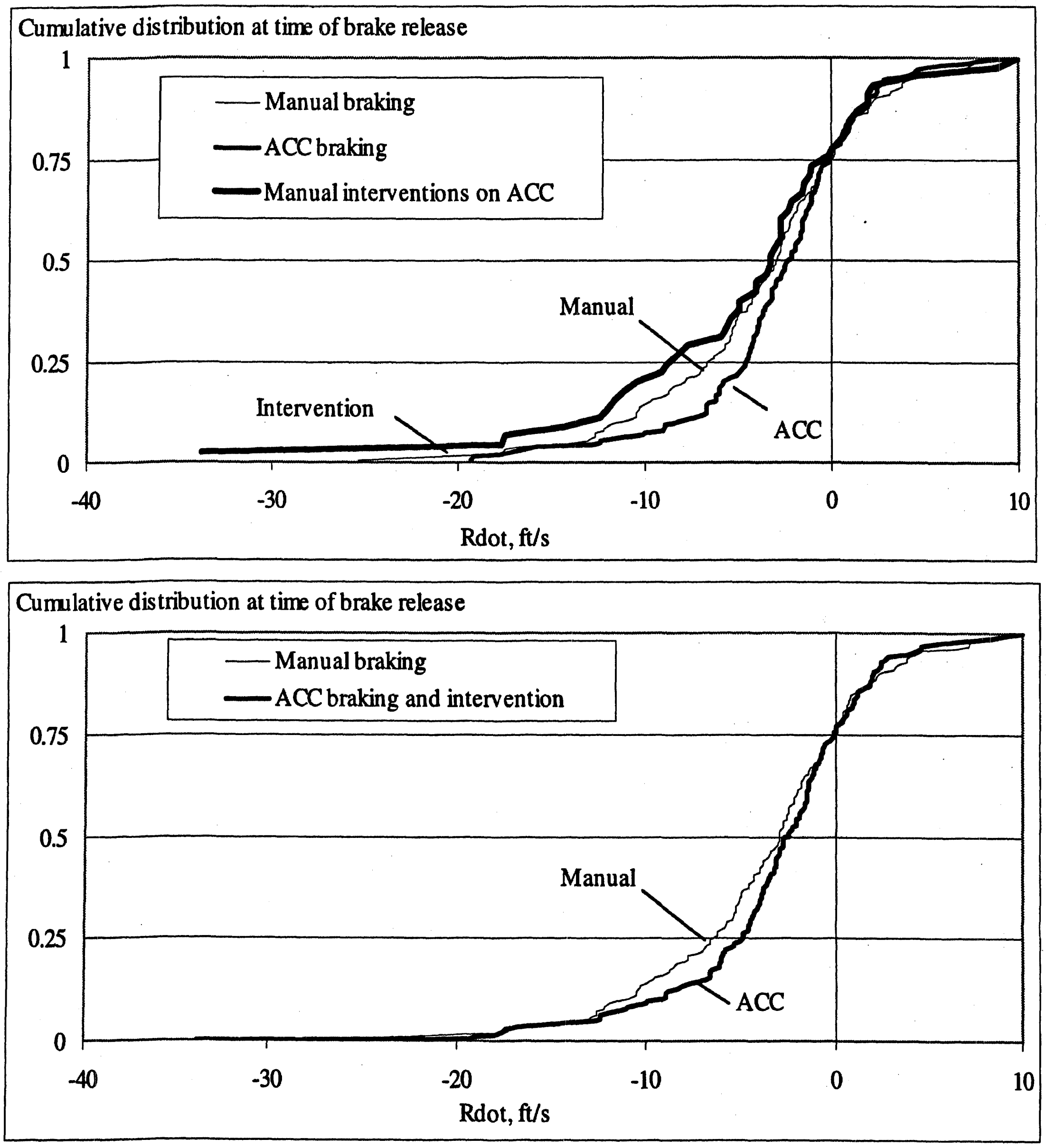


Figure 38. Results for Rdot at brake release

In the bottom plot in Figure 38, the ACC and intervention results have been combined into a single distribution to represent all the braking during the ACC loop. The idea here relates to the driving environment. The driving experiences are expected to be nearly the same for both the manual and ACC loops. The route and the car were identical for each time around the driving loop. Presumably, the traffic demands were the same, on average. This would mean that the ACC-plus-intervention curve and the manual curve would be nearly identical if the results were entirely controlled by the driving environment. The bottom plot in Figure 38 shows that the distributions for Rdot are different in the neighborhood of –5 to –10 ft/sec. Hence, the results are not entirely controlled by the environment. Driving with this ACC system and manual driving are different with regard to when the brakes are released.

How is the brake used?

This subsection addresses the levels of braking deceleration observed in manual, ACC, and intervention braking. Figure 39 shows cumulative distributions for minimum and average deceleration (where Vpdot < 0 represents deceleration and the minimum Vpdot represents the maximum deceleration). The values of deceleration shown in Figure 39 include amounts due to drag forces and brake forces combined.

Clearly, intervention braking was more frequent at greater levels of deceleration than it was in either manual or ACC braking. In general, manual braking involves higher levels of deceleration at a given frequency than the levels applied in ACC braking. For example, the 25th percentile level for manual braking corresponds to approximately – 0.19 g while the 25th percentile value corresponds to approximately 0.14 g for ACC braking.

It is reassuring to see that the minimum observed Vdot for ACC braking was –0.22 g. This shows that the system performs in accordance with the maximum deceleration authority prescribed for the system.

The results for the average deceleration (in Figure 39) are qualitatively similar except the values of deceleration are smaller. This means that the braking is not uniform at a constant level throughout each braking event. There can be large spikes compared to the average level of deceleration.

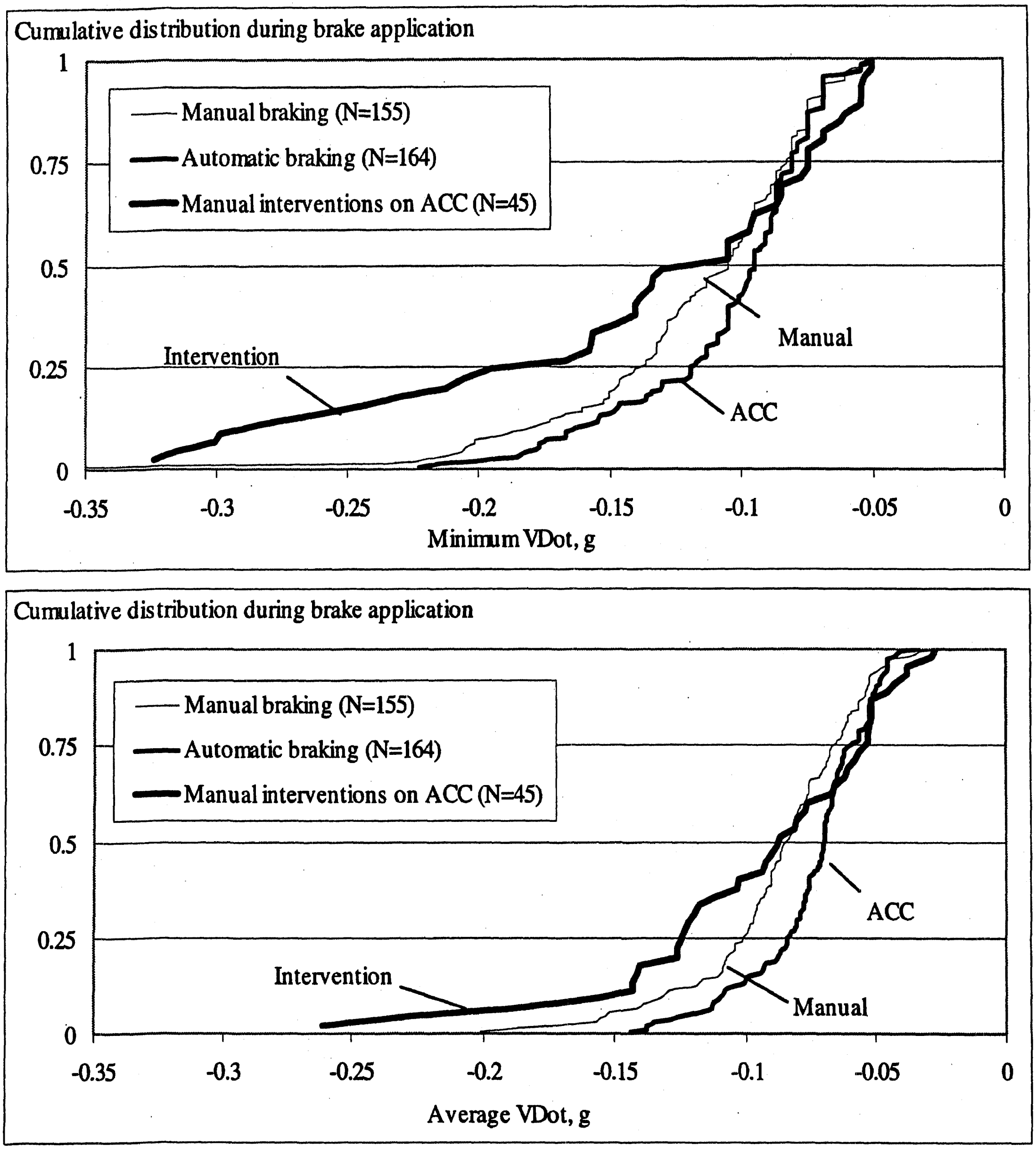


Figure 39. Minimum and average deceleration during brake applications

Figure 40 shows results that are intended to see whether differences are due to the environment or the braking mode. As discussed previously, if the environment completely controlled the situation, then the braking characteristics would be the same regardless of the type of braking. The results presented in Figure 40 indicate that the environment does not entirely control braking frequencies at minimum or average Vdot levels near –0.1 g. However, examination of the distributions for minimum Vdot indicates that they are somewhat alike.

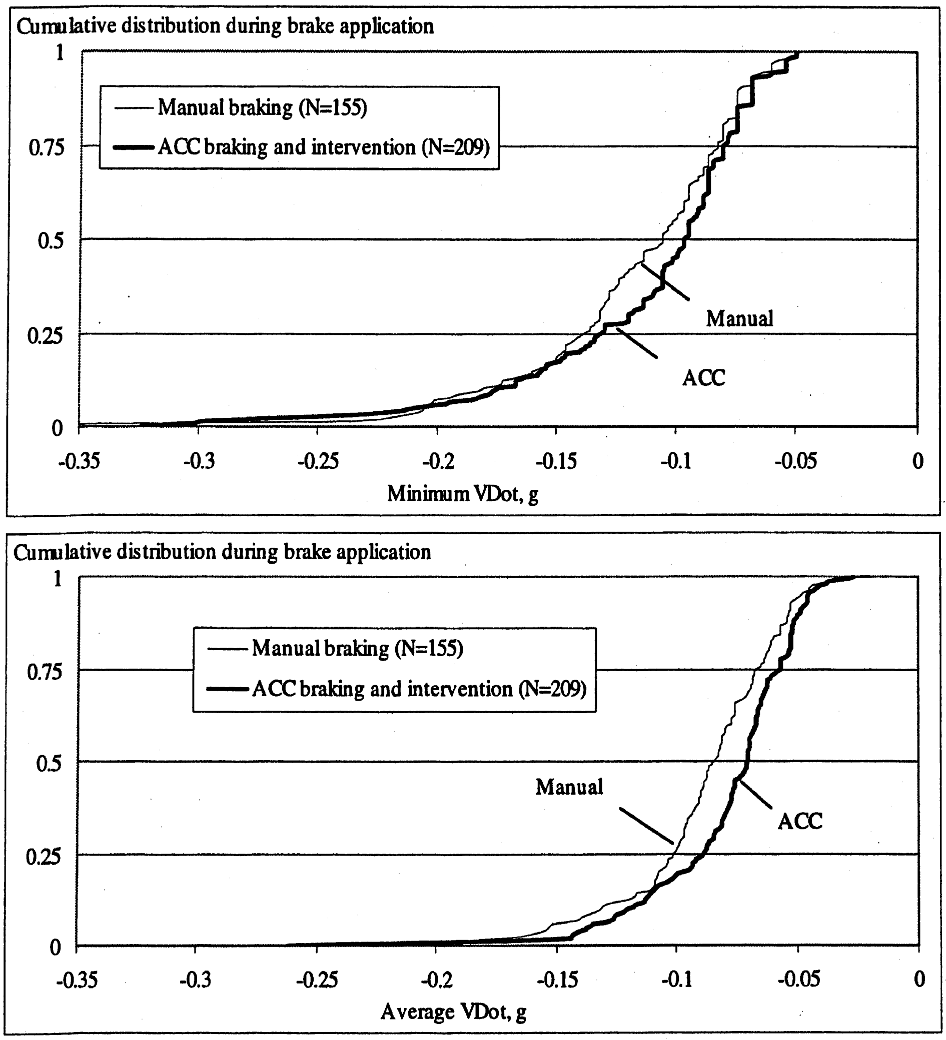


Figure 40. Combined ACC braking and intervention results for minimum and average Vdot.

5.2.4.10 Small Multiples for each FOCAS driver

The following results show differences and similarities in the observed behavior of each driver. Manual and ACC driving behavior is displayed for all drivers using miniatures of headway-time-margin, time-to-collision, and velocity results for each driver.

Headway-time-margin in following

Results for headway-time-margin are presented in Figure 41. The data used in these results pertain to the following situations only. This means that range-rate was near zero (|Rdot| < 5 ft/sec) and that Htm was at least 0.5 seconds. The idea is to examine how drivers tend to follow other vehicles. We will examine time-to-impact during closing operations to determine how drivers tend to close on preceding (impeding) vehicles. (See reference [1] for a discussion of the following and closing regions.)

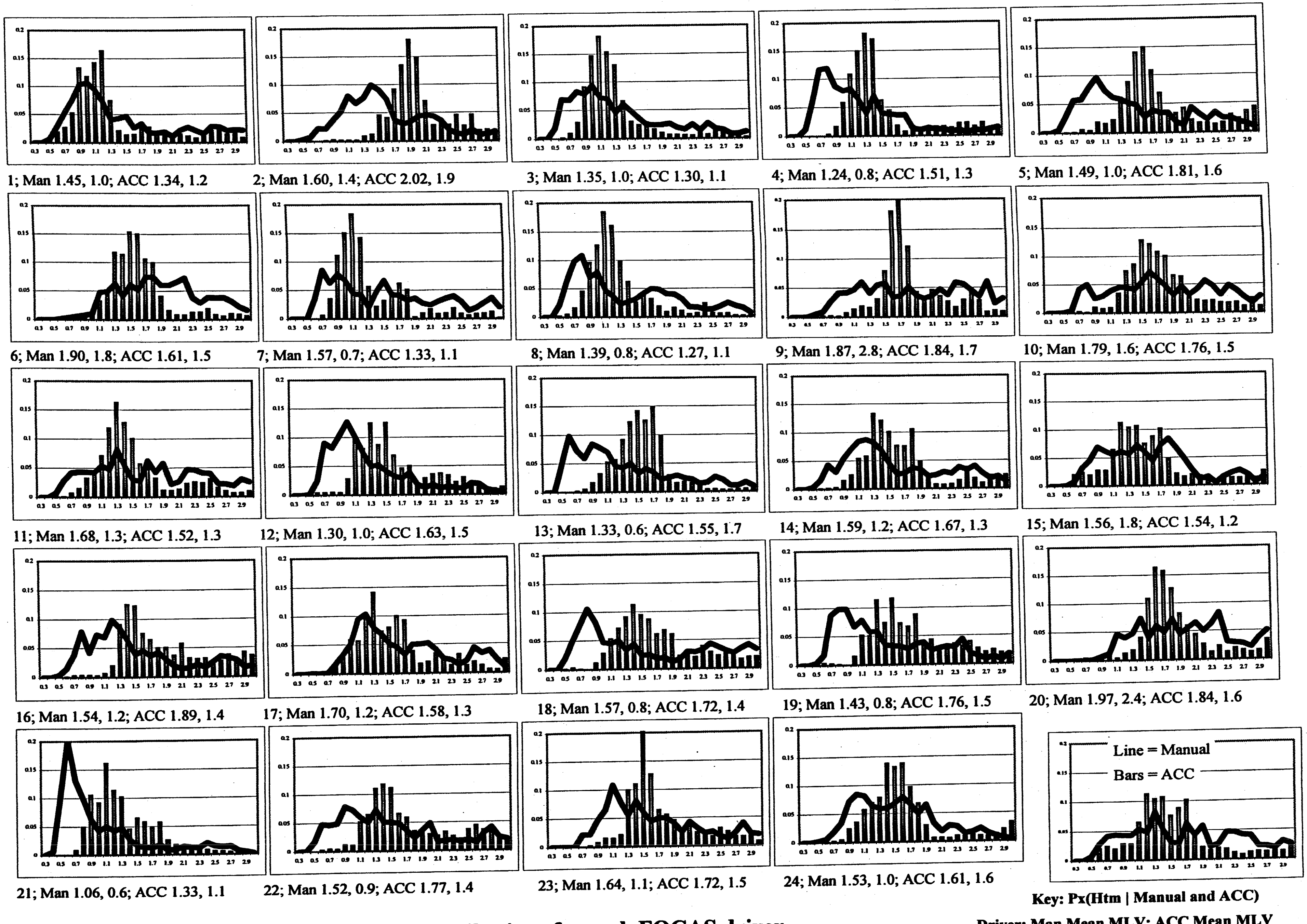


Figure 41. Manual and ACC Htm distributions for each FOCAS driver.

Examination of Figure 41 reveals that there is considerable white area between the manual (solid lines) and the ACC (vertical bars) at low levels of Htm. This is because the minimum headway-time setting for this ACC-with-braking system was 1.0 seconds. The results in figure 18 indicate that many drivers frequently drove manually with short headway times.

Table 6 provides a numerical comparison between manual and ACC driving for headway-time-margins less than 1 second. Inspection of the table indicates that only drivers 1, 3, 7, 8, and 21 spent more than 10 percent of their time in ACC driving below Htm = 1.0 second. When driving manually, each of these drivers spent a greater percentage of their time at Htm levels below 1.0 second. Only drivers 6, 17, and 20 had 5 percent or less of their manual driving at values of Htm that were below 1.0 second. The averages (for percent of time less than Htm =1.0 across all drivers) are 27.1 percent for manual driving and 5.3 percent for ACC driving. Clearly, ACC driving aids drivers by reducing the amount of exposure to short headway time situations.

Table 6. Percent Htm less than 1.0 s

Driver	Manual	ACC
1	27	23
2	9	0
3	32	13
4	39	2
5	23	1
6	2	1
7	26	15
8	36	16
9	8	1
10	12	1
11	16	6
12	30	2
13	36	2
14	15	2
15	16	9
16	18	1
17	5	5
18	33	2
19	30	1
20	1	1
21	60	16
22	24	2
23	9	1
24	13	3
Avg.	21.7	5.3

In contrast, Table 7 indicates that the mean values for Htm are quite similar for manual and ACC driving. The averages are 1.54 seconds for manual driving and 1.62 seconds for ACC driving. This indicates that the flow of traffic under these moderate-density conditions would not be affected much by the use of this ACC system. Although the frequency of short headway times was greatly reduced by ACC, the average was not changed substantially. (Also, the velocity results presented later indicate that the average speed is slightly higher for ACC driving. Hence, the net throughput would be nearly the same for ACC or manual driving under these conditions.)

Table 7. Mean Htm values, s

Driver	Manual	ACC
1	1.45	1.34
2	1.60	2.02
3	1.35	1.30
4	1.24	1.51
5	1.49	1.81
6	1.90	1.61
7	1.57	1.33
8	1.39	1.27
9	1.87	1.84
10	1.79	1.76
11	1.68	1.52
12	1.30	1.63
13	1.33	1.55
14	1.59	1.67
15	1.56	1.54
16	1.54	1.89
17	1.70	1.58
18	1.57	1.72
19	1.43	1.76
20	1.97	1.84
21	1.06	1.33
22	1.52	1.77
23	1.64	1.72
24	1.53	1.61
Avg.	1.54	1.62

The most-likely-values (MLV) are given below each of the miniature histograms presented in Figure 41. These values provide an indication of the driver's desired headway time. They are not viewed as results from a completely random choice—especially when the histogram is skewed such that there is a distinct MLV that is substantially different from the mean value of headway-time-margin. Table 8 displays the

MLV data obtained while in the "Following" zone of the range versus range-rate diagram.

Table 8. Htm—Following MLV, s

Driver	Manual	ACC
1	1.0	1.2
2	1.4	1.9
3	1.0	1.1
4	0.8	1.3
5	1.0	1.6
6	1.8	1.5
7	0.7	1.1
8	0.8	1.1
9	2.8	1.7
10	1.6	1.5
11	1.3	1.3
12	1.0	1.5
13	0.6	1.7
14	1.2	1.3
15	1.8	1.2
16	1.2	1.4
17	1.2	1.3
18	0.8	1.4
19	0.8	1.5
20	2.4	1.6
21	0.6	1.1
22	0.9	1.4
23	1.1	1.5
24	1.0	1.6
Avg.	1.2	1.4

Inspection of Table 8 and examination of Figure 41 indicate that many drivers tend to seek headway times less than 1.0 second when driving manually. Driver 21 is an extreme example. Drivers 4, 8, 13, 18, and 19 also show strong tendencies to operate at headway times less than 1.0 second.

Time-to-collision in closing

Figure 42 provides miniatures showing cumulative distributions of Ttc in manual and ACC driving for all 24 drivers. These results only use data pertaining to closing situations in which Rdot is less than –5 ft/sec.

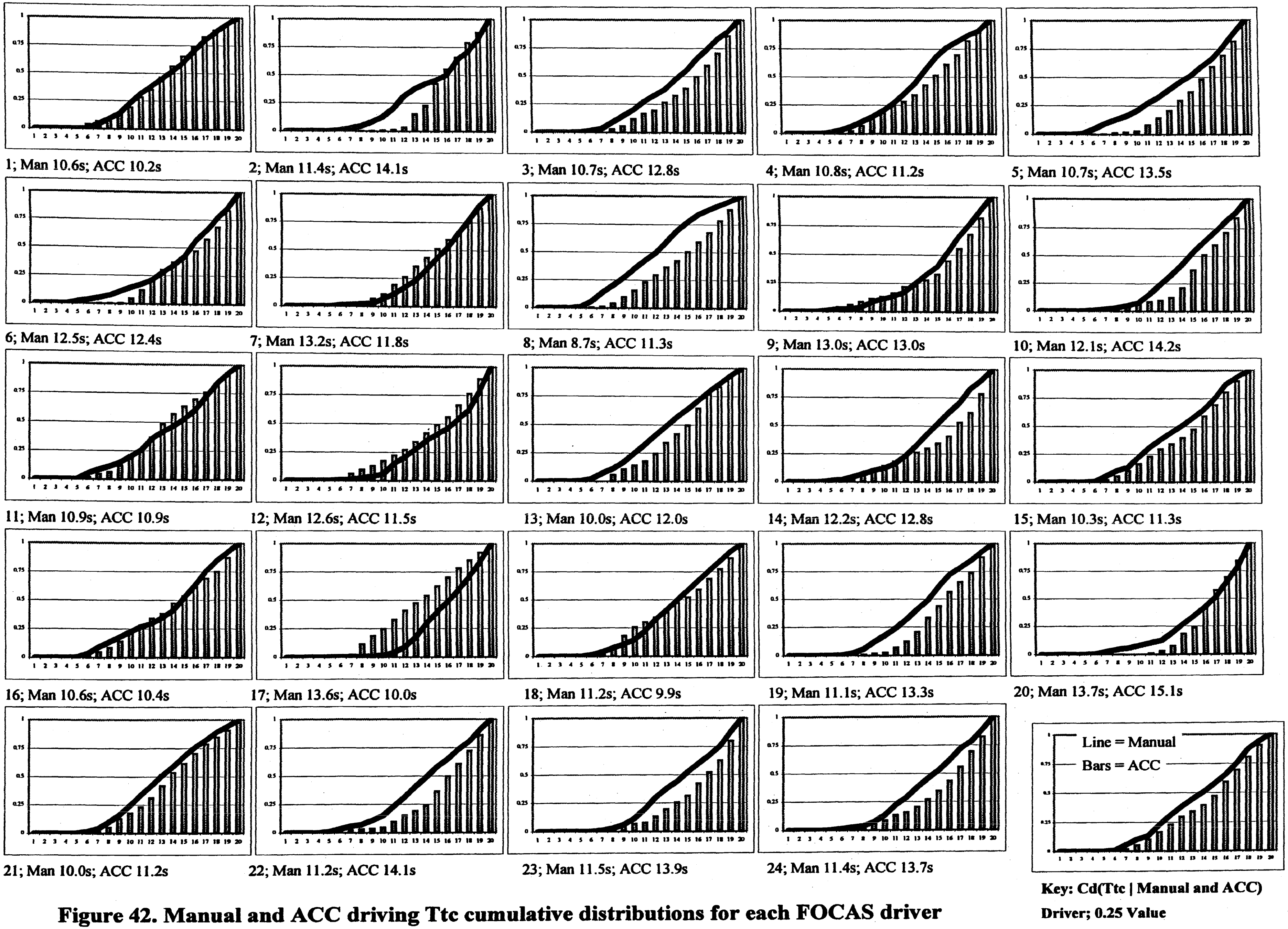


Figure 42. Manual and ACC driving Ttc cumulative distributions for each FOCAS driver

Listed below each miniature in Figure 42 are the 25 percentile values for Ttc. These values are tabulated in Table 9 to make inspection easier.

Table 9. Ttc — Closing, 25th percentile values, s

Driver	Manual	ACC
1	10.6	10.2
2	11.4	14.1
3	10.7	12.8
4	10.8	11.2
5	10.7	13.5
6	12.5	12.4
7	13.2	11.8
8	8.7	11.3
9	13.0	13.0
10	12.1	14.2
11	10.9	10.9
12	12.6	11.5
13	10.0	12.0
14	12.2	12.8
15	10.3	11.3
16	10.6	10.4
17	13.6	10.0
18	11.2	9.9
19	11.1	13.3
20	13.7	15.1
21	10.0	11.2
22	11.2	14.1
23	11.5	13.9
24	11.4	13.7
Avg.	11.4	12.3

Examination of Figure 42 indicates that Ttc for manual and ACC driving appears to be nearly the same for many drivers. For examples, see the results for drivers 1, 4, 6, 9, 11, 14, and 16. Inspection of Table 9 indicates that the 25th percentile values for these drivers are nearly equal.

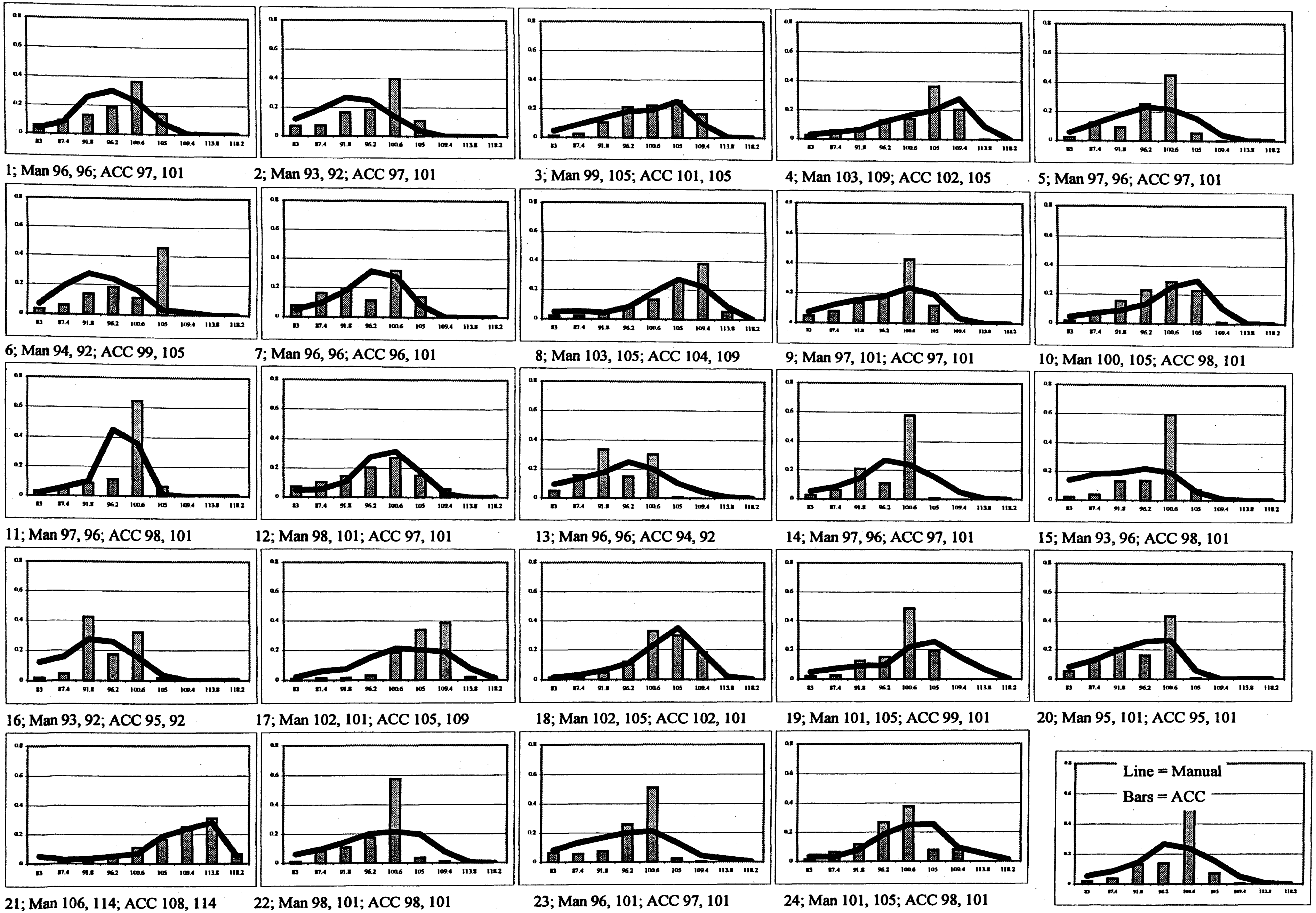
Further inspection of Table 9 reveals differences between manual and ACC driving for many drivers. It can be seen in Figure 42 that these differences may involve either Ttc for manual driving being larger than Ttc for ACC driving or the other way around. As listed in Table 9, the largest 25th percentile value for Ttc in manual driving was 13.7 s for driver 20. The smallest value was 8.7 s for driver 8. In ACC driving, the largest was 15.1 s for driver 20 and the smallest was 9.9 s for driver 18. There were 4 drivers for which

Ttc for manual driving exceeded their Ttc for ACC driving, however, there were 13 drivers for which their ACC value exceeded their manual value. The averages of the Ttc values were 11.4 s for manual driving and 12.4 for ACC driving.

These results indicate that, with regard to time-to-collision in closing situations, the ACC system performed in a manner that is similar to the way drivers behave under the manual control mode. The measured results for the ACC system correspond roughly to the slope chosen for the dynamics line in the design of the ACC system. The dynamics line has a time constant of 11.0 seconds, which is close to the 25th percentile values measured in these tests. Based on the results shown, it is proposed that drivers have a lower bound on closing rate that they do not like to cross. The evidence reported here tends to support this proposition.

Velocity above 55 mph (80 ft/sec)

Velocity was chosen as the third variable to consider in this topic area because reasoning with regard to visual perception indicates that drivers may perceive velocity through a streaming effect detected at the eyeball. In the FOCAS program, the looming effect has also played a major role in our thinking. This effect can be used to propose that drivers have a direct visual sensation of the time-to-impact from the looming properties of the preceding vehicle as projected onto the eye. In addition, by observing stationary objects at the same range as the preceding vehicle, drivers may obtain a looming sensation that corresponds to headway-time-margin. The point is that driver skill in going from the driver's eyes to the driver's feet may be explained in terms of velocity, Ttc, and Htm. (See section 6 for further discussion of matters pertaining to how people control their speed and distance in driving situations.) Figure 43 presents histograms showing speed characteristics for manual and ACC driving on freeways, displayed as miniatures for each driver. The bars representing ACC driving often have a bin that contains the driver's preferred speed. The bar corresponding to this bin is much higher than the other bars in these cases. For examples, see the results for drivers 1, 2, 4, 5, 6, 9, 11, 14, 15, 19, 20, 22, and 23 in the figure. These observations indicate that in ACC driving many drivers appear to use a preferred set speed that is close to the normal speed of traffic flow on these freeways.



Key: Px(Velocity | Manual and ACC)
Driver; Man Mean MLV; ACC Mean MLV

Figure 43. Manual and ACC velocity histograms for each FOCAS driver

The solid lines corresponding to manual driving in the figure show some peaking at a preferred speed but these histograms are relatively flat compared to those for ACC driving. Further, detailed findings with respect to speed may be discovered by inspecting Table 10.

Table 10. Mean velocity values, ft/sec

Driver	Manual	ACC
1	95.6	97.2
2	92.8	96.6
3	98.7	100.8
4	103.0	101.6
5	96.5	96.9
6	93.7	99.1
7	95.9	95.5
8	102.6	104.5
9	96.7	97.2
10	99.7	98.3
11	96.7	98.3
12	97.9	96.9
13	95.5	94.1
14	97.3	97.0
15	93.5	98.3
16	93.0	95.3
17	101.8	105.1
18	102.3	102.2
19	101.0	99.0
20	94.8	95.4
21	106.5	108.3
22	97.7	97.8
23	96.3	97.0
24	100.9	98.3
Avg.	97.9	98.8

These results indicate that drivers 2, 6, 15, and 16 tended to travel slowly compared to the average of 97.9 ft/sec for manual driving. Driver 21 stands out (as seen before) driving manually at considerably higher speeds than those used by the other drivers. In general, these 24 drivers tend to drive faster under ACC control. The average for ACC driving is 98.8 ft/s, compared to 97.9 ft/s for manual driving. This result corresponds to the reported perception (see question 10 of the subjective results) of traveling faster in the ACC mode compared to manual control. Although this speed advantage is not a big thing, it counters the perception that cut-ins constitute a major loss of time. There does not appear to be an important loss of time due to cut-ins.

5.1.5 Findings and Recommendations

The results show the following:

1. in general, the ACC-with-braking system is given high subjective rating with respect to safety, comfort, and convenience—drivers like it!
2. statistical analysis of the subjective ratings resulted in eight statistically significant findings:
   - young and middle-aged drivers felt safer in manual while older drivers felt safer in ACC
   - with the exception of middle-aged females, all drivers found ACC to be comfortable
   - all drivers found ACC to be more convenient than manual driving
   - young drivers reported that they tend to drive slower with ACC relative to manual, whereas, middle-aged and older drivers reported driving faster in ACC
   - older drivers reported feeling that they did not understand what the ACC system was doing, or how it might behave, more frequently than young or middle-aged drivers
   - all drivers reported that they felt more comfortable passing while driving manually as opposed to driving with ACC
   - female drivers reported that the ACC system functions were more distracting than did male drivers, and
   - female drivers reported that the ACC system components were more distracting than did male drivers
3. statistical analysis of the participant's measured variables yielded the following observations: a) male drivers maintained a 14.4 ft shorter range, a 0.14 s shorter headway-time-margin, and drove nearly 3 ft/s faster than did female drivers under similar conditions and b) young drivers drove significantly faster than either the middle-aged or older drivers.

4. two-dimensional histograms using normalized headway-time-margin and range-rate show that the ACC-with-braking system is very good at keeping headway-time-margin close to the headway time setting chosen by the driver.

5. the ACC system, created and implemented by UMTRI, satisfied its functional purpose of providing comfortable and convenient control of speed and range.

6. the concepts used in the design of this ACC system resulted in a system that satisfied its functional purpose with respect to Htm, Ttc, velocity, and acceleration.

7. throttle modulation in ACC-with-braking control appears to be less than in manual control. Average velocities were higher with ACC than manual yet the mean percent throttle was less in ACC than manual control. This suggests that ACC control may be more fuel efficient than manual control.

8. variations between individual drivers with regard to relative speed and range are reduced when driving with ACC as opposed to manual.

9. when comparing FOCAS to the ICC FOT results, drivers accompanied by a researcher did not tend to tailgate while driving manually. None of the FOCAS drivers had hunter/tailgater driving styles.

10. the ACC-with-braking system tends to constrain driving to a flow conformist style unless the driver chooses a set speed that is significantly faster or slower than that of the prevailing traffic stream.

11. distributions comparing manual braking to ACC braking (auto-braking) show similarities with regard to Htm values less than 1 s at the time of brake pedal application. (This suggests that the ACC control algorithm is braking at the same Htm as drivers do manually, at least for values of 1 s or less.)

12. Interventions on ACC tend to happen at larger negative range-rates and larger Htm values relative to manual and ACC braking which seems to indicate that the driver, at least in the FOCAS study, did not wait to see if the ACC system could handle a potential conflict.

13. with regard to time-to-collision (-Range/Range-rate) in closing situations, the ACC system performed in a manner that is similar to the way drivers behave.

14. these results and the findings in [11] show that drivers tend to brake in a manner that minimizes the loss of headway-time-margin.

5.2 Braking Latency

5.2.1 Research Activities

In the fifth year, we performed tasks involving data processing aimed at analyzing driver response delays and lane change characteristics. The latencies in staged stopping situations as well as in naturalistic driving were examined. We then formulated an approach for processing the ICC FOT data set to study braking latency with and without ACC as well as driver lane changing behavior with and without ACC. The ICC FOT database was processed according to data processing rules developed for this purpose. The data processing effort identified approximately 14,000 lane changes of which approximately 5,000 of them had a preceding vehicle in near proximity. The efforts regarding lead vehicle braking found 303 hard braking cases (where the deceleration level exceeded 0.1 g at initial speeds greater than 50 mph) in manual driving. There were 67 similar cases when the driver intervened by braking when the ACC system was in operation. (Detailed braking latency results for manual and ACC driving are presented in this report. Reference [11] is a prior report on the results of the braking latency and lane changing studies.)

5.2.2 Analysis Methodology

The ICC FOT data do not include a direct indication of when the driver of the preceding vehicle pressed on the brake pedal. The time when the brake lights of the preceding vehicle are illuminated is not automatically recorded. In addition the level of brake application is not measured. Hence it is necessary to compute an estimate of the deceleration rate of the preceding vehicle for use in identifying when and how much the preceding vehicle decelerates.

The method for determining the deceleration of the preceding vehicle is as follows. First the speed of the preceding vehicle is calculated using the velocity (V) of the vehicle equipped with the ACC system (the ACC vehicle) and the range-rate (Rdot) measured by the ACC sensor. (The sensor signals (range (R) and Rdot) and velocity V are measured regardless of whether the driver is driving manually or with the ACC system engaged.) The velocity of the preceding vehicle (Vp) is equal to the sum of V and the relative velocity Rdot between the vehicles. Hence,

$$Vp = V + Rdot \tag{5.2}$$

The calculated value for Vp is then differentiated numerically to obtain an approximation to Vpdot. Since the signals for V and Rdot are recorded, past and future values of Vp can be used in determining Vpdot at any chosen time. However, the resolution on V is to the nearest 0.5 mph and the data rate is 10 samples per second. This means that the raw Vpdot signal is quite noisy and can have frequent spikes as well as relatively long periods of zero acceleration. To compensate for this situation, smoothing and regression techniques are used to remove some of the higher frequency content from the Vpdot signal.

Furthermore drivers do not tend to brake with step-function responses. There are situations in which the driver coasts or brakes modestly before resorting to hard braking. When situations that start with modest braking arise, it is difficult to choose a value for the time when hard braking started. A special technique was devised in this study to identify and assign the time when the preceding vehicle started to decelerate rapidly. This same technique was also used to assign and identify the time when the ACC-equipped vehicle started to decelerate rapidly.

The procedures for determining the times when significant decelerations were initiated are shown in Figure 44. The figure is divided into three plots and shows a braking event for FOT driver 59 on trip 67 at a time of 14.06 minutes [1]. The top plot shows acceleration for the ACC and preceding vehicles along with the brake signal indicating application of the brake pedal in the ACC vehicle. The center plot shows the velocity of the ACC and preceding vehicles along with four constant-slope best-fit lines (two lines for each signal). The bottom plot shows range and range-rate during the braking event.

The basic idea is to fit two straight-line segments to the velocity signal. The first line is fitted to the velocity signal prior to a rapid deceleration. The second line is fitted to the velocity signal during the time of rapid deceleration. The slopes of these lines indicate an approximation to the deceleration before (slope m1) and during braking (slope m2). The time corresponding to the point where these lines intersect is taken as the time when significant deceleration starts.

Thus for selected braking events there is a time called the preceding vehicle intersection time that indicates approximately when the preceding vehicle started to decelerate significantly. There is also a similar time called the ACC vehicle intersection time. For a particular braking event, the difference between ACC vehicle intersection time and the preceding vehicle intersection time is called the wait time (Wt). Hence, wait time (Wt) is a measure of how long the driver waited before intervening with significant braking in the situation being examined. (Wait time is the center plot of Figure 44.)

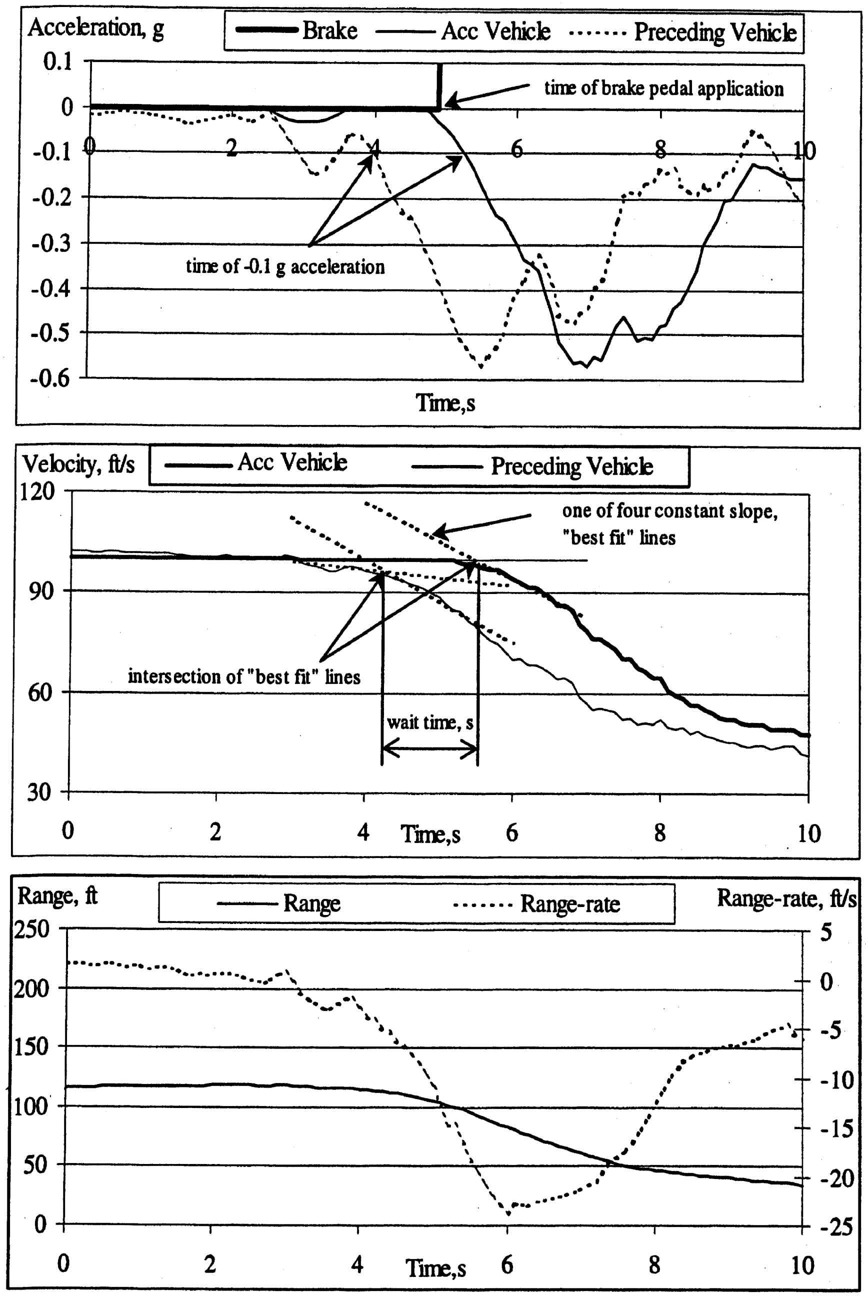


Figure 44. Illustration of wait time calculation

The results section of this report presents a set of braking events that satisfy the following inequalities:

$V \geq 50$ mph (80 kph) at the ACC vehicle intersection time and

$-0.05g \leq m1 \leq 0.0g$ and $m2 \leq -0.1g$ for both Vp and V.

These inequalities require that the vehicles are traveling at highway speeds and that they are braking at a relatively hard level.

5.2.3 Results

The entire set of data measured in the FOT covered approximately 114,000 miles of driving by 108 different drivers in normal transportation service [1]. The data analysis found 67 hard braking cases during ACC driving when the ACC system was operating on a target. There were 303 such cases during manual driving.

Although drivers tended to drive manually or use ACC with approximately equal frequency in the speed range above 50 mph, it was observed in the FOT study that drivers tend to use ACC when they believe that braking will not be necessary. In general, they tend to operate manually when the situation is more difficult to predict. Nevertheless, regardless of whether the driver is using ACC or not, braking events where both the preceding and the following vehicle decelerate at a magnitude greater than 0.1 g are relatively infrequent events at speeds above 50 mph.

Table 11 presents a summary of results including averages and standard deviations of pertinent quantities for the sets of manual and ACC brake interventions. Examination of the table indicates that on average the ACC braking cases appear to be slightly more severe than the manual cases because the decelerations are slightly larger and the relative velocities (Rdot) are more negative. (Negative Rdot indicates that range to the preceding vehicle is getting smaller.)

Table 11. Summary of results for ACC and manual brake interventions

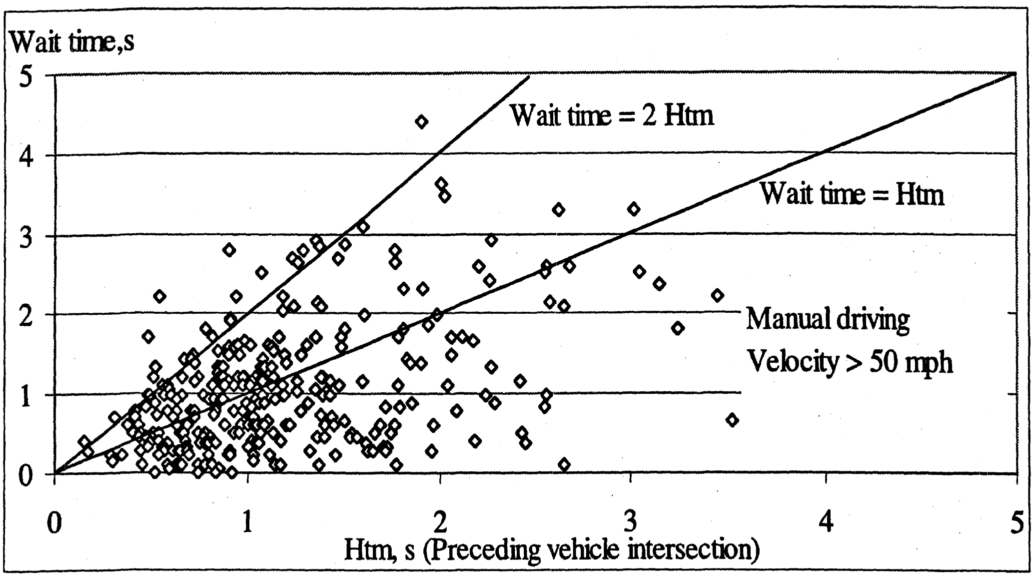
		Wait time and other statistics during brake application time				
		Wait time, s	Delta V, ft/s	Brake time,s	Decel., g	Max decel, g
Manual	Average	1.05	22.66	4.49	0.16	0.25
	Std dev	0.81	17.94	3.51	0.05	0.09
ACC	Average	1.26	32.06	6.10	0.17	0.27
	Std dev	0.91	20.92	4.70	0.06	0.09
		Preceding vehicle intersection				
		Range, ft	Rdot, ft/s	Velocity, ft/s	Htm, s	Tti, s
Manual	Average	102.23	-3.48	87.65	1.18	23.12
	Std dev	55.34	4.52	10.14	0.65	11.40
ACC	Average	144.50	-5.20	91.39	1.59	23.25
	Std dev	66.09	6.36	9.67	0.73	11.80
		ACC vehicle Intersection				
		Range, ft	Rdot, ft/s	Velocity, ft/s	Htm, s	Tti, s
Manual	Average	92.89	-7.89	86.42	1.09	14.72
	Stand dev	47.26	5.75	10.07	0.57	8.57
ACC	Average	129.99	-11.42	90.26	1.44	14.69
	Stand dev	58.30	7.98	9.95	0.64	10.41

In addition, the brake time (that is the duration of the braking period for the ACC-equipped vehicle) is longer for the ACC cases than it is for the manual driving cases. Hence the speed change (delta V) for the ACC-equipped vehicle is greater for ACC driving than it is for manual driving. However, the standard deviations for these results are so large that the differences in the averages may not be regarded as statistically trustworthy.

Table 11 also contains results pertaining to the headway situation at the preceding vehicle and ACC vehicle intersection times. Again the standard deviations are large compared to the average values, but on average the headway distances (R) and headway-time-margins (Htm = R/V) are larger for ACC driving. The additional headway-time-margin for ACC driving means that the ACC system provides more time to react than that which drivers choose to use in manual driving.

Table 11 contains results for time-to-impact (Tti = -R/Rdot) but they do not appear to provide us with any useful interpretation except that they seem to be relatively large and benign when the preceding vehicle commences to decelerate rapidly. The results indicate that there were only two cases (both manual driving) in which time-to-impact (-R/Rdot) was less than 6 sec. However, data shown in Table E-1 of Appendix E indicate that time-to-impact values that are less than 6 seconds are not uncommon by the time the ACC-equipped following vehicle starts to brake heavily.

Figure 45 is based upon data gathered at the beginning of the braking event (that is, at the preceding vehicle intersection time). There are no data points in the region of the figure characterized by relatively long wait time compared to the headway-time-margin. Qualitatively, this is because the driver does not wait very long if the headway-time-margin is small—otherwise the driver would come close to crashing. However, there are many wait times that are longer than the headway-time-margin as indicated by the superimposed line with a slope of unity passing through the point, Htm = 5 and Wt = 5 in Figure 45.



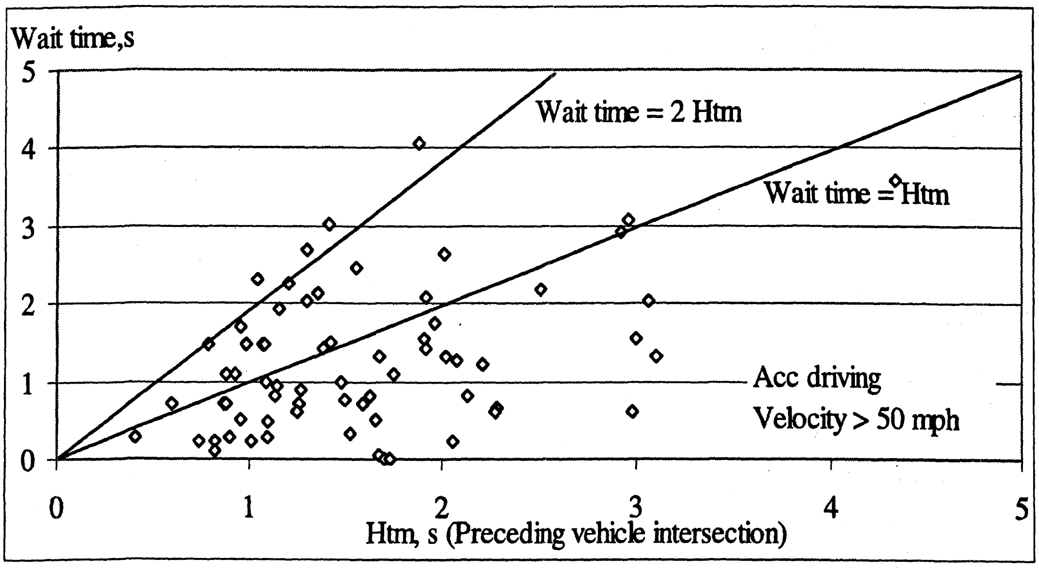


Figure 45. Wait time versus headway-time-margin at the preceding vehicle intersection time

Figure 46 is similar to Figure 45 except the variable used for the horizontal axis is Htm at the time when the ACC-equipped vehicle starts hard braking. Overall the appearance of Figure 45 and Figure 46 are similar. However, an important difference is shown in Figure 47.

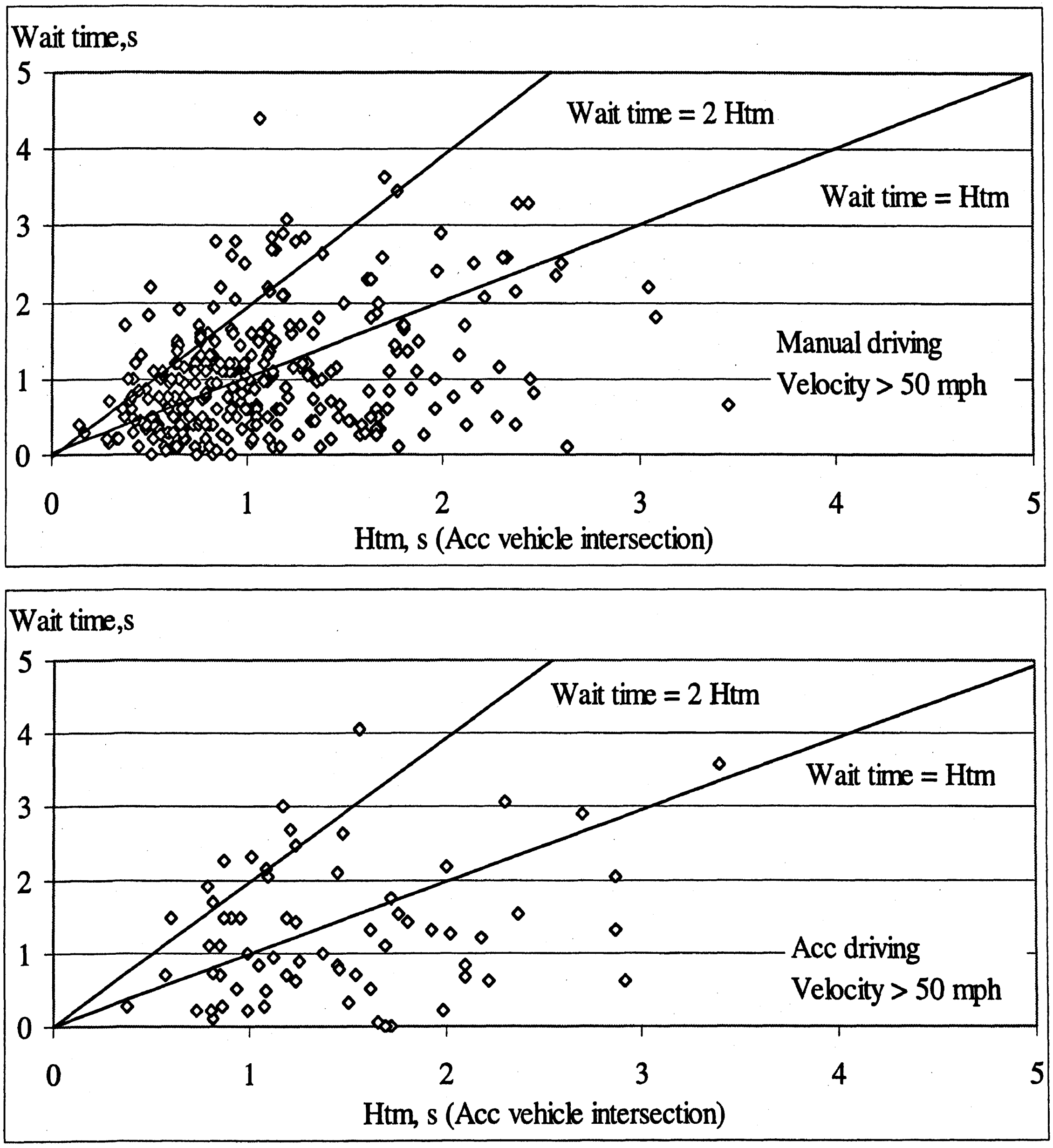


Figure 46. Wait time versus headway-time-margin at the ACC vehicle intersection time

Figure 47 shows that the driver does not wait so long that the headway-time-margin changes by much more than 0.2 times the wait time. This result indicates a tendency for drivers to try to maintain headway-time-margin by braking promptly when necessary.

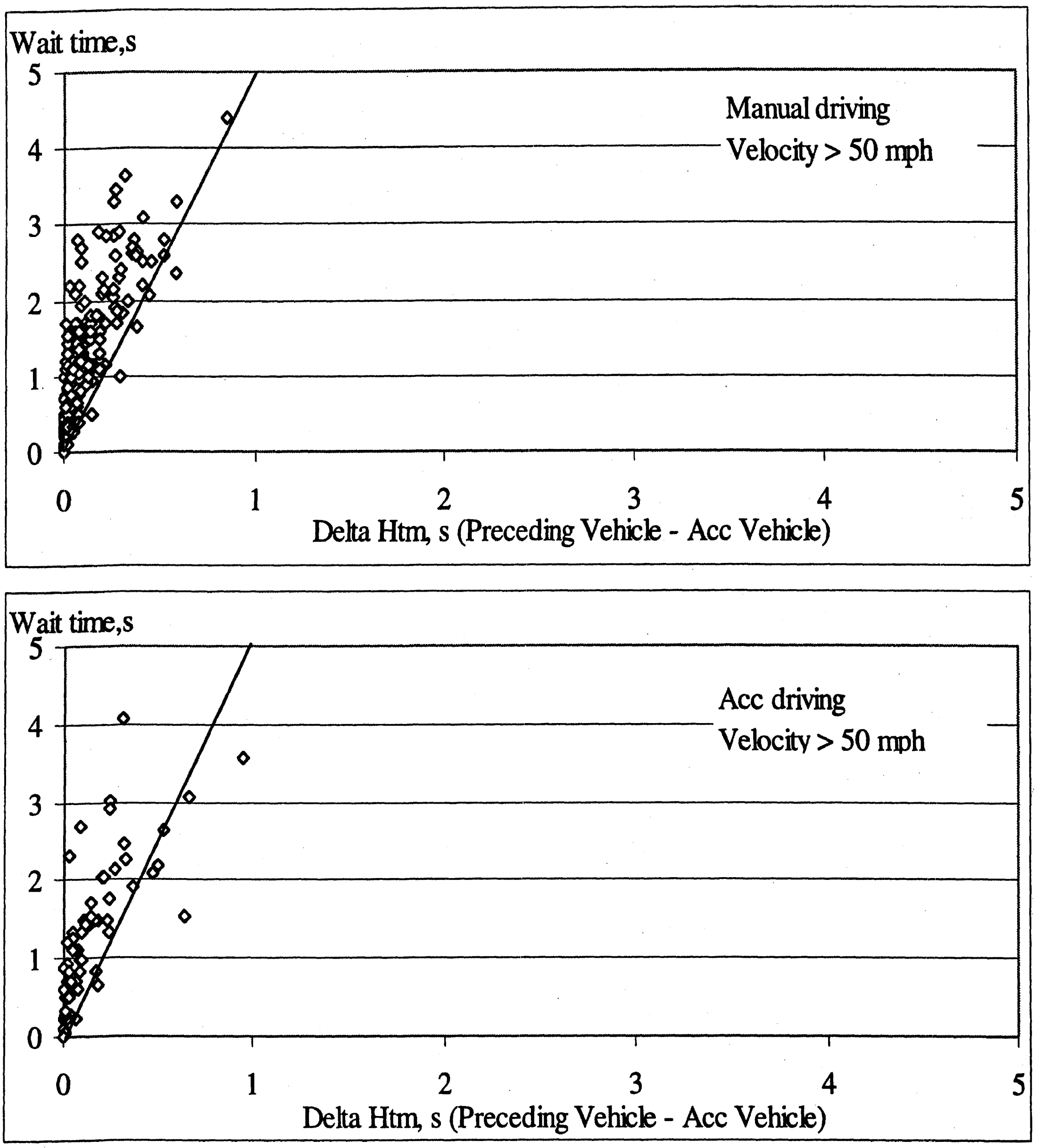


Figure 47. Change in wait time versus headway-time-margin

The physical basis for comparing the wait time with the headway-time-margin lies in the following observation. If the preceding and following vehicles are initially traveling at approximately the same speed at a constant range, the headway-time-margin would be R/V = Htm. Then, let us assume that the preceding vehicle braked at nearly a constant deceleration Dp, and the following vehicle delays any braking for Htm seconds but then the following vehicle brakes at the rate Dp also. In this scenario the vehicles would not crash but the front of the following vehicle would end up next to the rear of the preceding vehicle, if both vehicles proceeded to a stop. Hence one might expect Htm to be something like the wait time if this scenario were representative of the test results.

Examination of Figure 45 shows that the data are spread about the line of unity slope (Htm = wait time) with points ranging from $Wt \approx 0$ to $Wt \approx 2 \cdot Htm$. This means that on occasion (when $Wt \approx 0$) the driver of the following vehicle braked at practically the same time as the driver of the preceding vehicle. In these cases, it is postulated that the driver of the following vehicle saw and knew of the impediment that caused the preceding vehicle to brake. The driver of the following vehicle was essentially responding to the impediment and not to the braking of the preceding vehicle per se. At the other extreme when $Wt \approx 2 \cdot Htm$, the driver of the following vehicle waited for what appears to be an exceptionally long time after the preceding vehicle started to decelerate rapidly. In these cases, it seems that the driver of the following vehicle would need to brake much harder than the driver of the preceding vehicle to avoid a near miss.

The following idealized analysis provides a basis for thinking and reasoning about the relationship between Htm and Wt. The analysis has been simplified by considering the equations for constant deceleration stops. Hence it constitutes a substantial abstraction from the realities of the situations in which the data were obtained. Nevertheless it serves as a reference for use in examining certain aspects of driver braking behavior.

A standard stopping distance equation for the following vehicle is:

$$Xf = Wt \cdot Vo + \frac{Vo^2}{(2 \cdot Ax)} \tag{5.3}$$

where Xf is the total distance covered by the following vehicle during the stop,

Vo is the velocity before and up to the time when braking started, and

Ax is the deceleration level of the following vehicle ($Ax > 0$).

The stopping distance available to the following vehicle is the initial range to the preceding vehicle (Ro) plus the stopping distance of the preceding vehicle, viz.,

$$Xp = Ro + \frac{Vo^2}{(2 \cdot Axp)} \tag{5.4}$$

where Axp is the deceleration level of the preceding vehicle ($Axp > 0$).

Clearly $Xf = Xp$ if $Ax = Axp$ and $Ro = Wt \cdot Vo$. Since Ro/Vo is equal to Htm at the time hard braking started, the unity slope line, as presented earlier in Figure 46, corresponds to this analytical result.

But what if Wt is greater than Htm? What do equations 5.3 and 5.4 imply about the relationship between Ax and Axp? To answer these questions, consider what equations 5.3 and 5.4 imply if Xf is set equal to Xp. After performing several algebraic steps the following equation is obtained:

$$\frac{Ax}{Axp} = \left[\frac{1}{(1 + (Axp \cdot 2 \cdot \frac{(Htm - Wt)}{Vo}))} \right] \tag{5.5}$$

Examination of equation 5.5 indicates that if Wt > Htm , Ax will be greater than Axp. Equation 5.5 also indicates that if Wt < Htm, Ax < Axp. However, in non-critical situations, the driver can choose to decelerate slightly harder than necessary without any serious consequences. Nevertheless, even though equation 5.5 is an idealized abstraction, it has relevance to driver behavior in cases where Wt is enough larger than Htm that Ax needs to be large to prevent a close encounter or a crash.

Examination of the data in Figure 45 indicates that rarely does the driver get into situations where Wt is greater than 2·Htm. Also examination of Table E-1 of Appendix E shows that the ratio of the initial deceleration of the following vehicle (as represented by M2_following) is seldom greater than twice the deceleration of the preceding vehicle (as represented by M2_preceding).

Table E-1 of Appendix E presents a comprehensive set of data for all 303 manual cases with hard braking as well as the 67 cases for ACC driving.

The results and findings presented next have been obtained by sorting the table in various manners. The version given in Appendix E has been sorted by values of Htm – Wt in ascending order. This choice of sorting is based upon the relationship given in equation 5.5.

The table contains values of pertinent variables such as R, Rdot, V, Htm, and Tti as well as M2 for the preceding vehicle at the preceding vehicle intersection time (when the preceding vehicle started to brake at 0.1 g or greater). The table also contains values of the same variables as well as M2 for the ACC-equipped vehicle at the ACC vehicle intersection time (when the ACC-equipped vehicle started to brake at 0.1 g or greater). In addition, values of the maximum deceleration for each vehicle (Max Ax) during each braking event are included in the table.

The data for each stop have been processed to determine the wait time (Wt), Htm – Wt, the change in speed of the ACC-equipped vehicle, and the time period of brake application for the ACC vehicle. In addition, three deceleration ratios have been computed:

1) "Slope Ratio" which is the ratio of the initial decelerations given by M2 (ACC vehicle) divided by M2 (preceding vehicle).
2) "Max Ratio" which is the ratio of Ax maximum for the ACC vehicle divided by Ax maximum for the preceding vehicle.
3) "Est. Ax Ratio" which is calculated from measured results using equation 4 to estimate the amount of braking just sufficient to avoid a crash if the initial braking by the preceding vehicle were to persist to a stop.

Clearly, we are trying to explain what has turned out to be a complex situation. There is a mixture of deterministic as well as probabilistic factors to consider. As in all events involving human psychology, one can only infer what the driver is thinking. We cannot measure what is in the driver's mind in the same manner as we can measure range (R) or some other physical quantity. Although we have a large amount of information concerning these braking situations, we only have limited knowledge concerning only a few of the many things the driver uses to decide on braking actions.

Simple results appear to explain something about wait times and deceleration levels in these braking events. However, the data are too scattered to fit a simple statistical analysis involving one or two variables. Given these difficulties, it seems surprising that sorting the processed data using various measured quantities and deceleration ratios provides interesting information. Perhaps, repeated ordering of the data by values of each variable has some utility as a practical, pragmatic approach to data mining in general. Nevertheless, a simple model such as that given by equation 4 is a great help in structuring the process of mining the data. There are too many possibilities to examine all possible relationships. In order to limit the number of possibilities to be examined, researchers need to select a strategy for trying to discover information that is useful to them. In this case our strategic goal is to find information that addresses whether drivers tend to wait too long and consequently brake too hard when ACC is in use.

5.2.4 Findings and Recommendations

The net conclusion from the examination of hard braking cases in both FOCAS and the ICC FOT is that the drivers do a remarkably good job of coping with braking events by the preceding vehicle. These data do not provide evidence supporting an expectation that ACC driving would be any less safe with regard to waiting too long before responding to braking by a preceding vehicle traveling at highway speeds. On the contrary, the additional headway time provided by the ACC system gives the driver more time to react. Furthermore, drivers appear to use this time in a manner that makes performance in ACC braking events much like that in manual braking events. (Although the examined manual events are believed to correspond to more conflicted traffic conditions than prevailed under ACC control.) The main difference between ACC and manual driving seems to be that there were fewer cases of hard braking in ACC driving than there were in manual driving during the ICC FOT and in the fifth year of the FOCAS study.

The results also demonstrate that the study of braking events is complex and multidimensional. Wait or driver lag time cannot simply be understood by looking at the time delay between decelerations of the preceding and following vehicles, regardless of how this delay is measured. Drivers brake for many reasons, only one of which is the slowing vehicle in front of them. Certainly, a critical objective in any braking scenario is to avoid a crash with the preceding vehicle, but this is only one of the objectives a driver uses when deciding when and how much braking to use in a given situation. It seems unlikely that any ACC system with its limited information on the whole environment at a given time will ever fully anticipate and control a vehicle in a manner similar to drivers—especially in non-highway applications where the driving environment is so complex.

5.3 NHTSA's Warning Algorithm

5.3.1 Research Activities

Investigation of the crash-warning application called for creating a new algorithm. In this case, the output of the algorithm not only controlled the vehicle, but it also activated a warning buzzer. The philosophy of a specific crash-warning design of interest here (often referred to as the NHTSA algorithm) can be stated as follows: *based on the current headway situation, we shall warn the driver if within 1.5 seconds from now he must apply at least 0.75 g braking to avoid getting closer than 7 ft to the vehicle ahead.* The specific values stated above represent parametric values that can be modified in the algorithm.

Employing the crash-warning model described above requires a computation of the deceleration of the lead vehicle. Several differentiation algorithms were developed, however, it became evident that the onboard computing power of the ACC system is not sufficient. The differentiation schemes were elaborate, proper filtering had to be applied to the data, and ACC commands also had to be computed within the allocated time period (0.1 second, since the system operates at 10 Hz.) To remedy the problem, special software was developed for use on a portable computer that had enough computing power. The laptop computer received the data from the ACC controller, processed it, and, if necessary, issued a warning. This external warning system configuration allowed for easy implementation of various schemes of crash warning. It also provided means for quickly adjusting parametric settings to accommodate different driving styles.

5.3.2 Analysis Methodology

5.3.2.1 NHTSA's Collision-Warning Concept

Development work was done concerning the NHTSA collision-warning concept. We implemented an initial version of an NHTSA-type collision-warning algorithm. We set up code that projects the current driving situation into the future. The time to reach a situation in which the driver needs to apply 0.75 g to avoid coming closer than 2 meters to the preceding vehicle is then calculated. If this time is less than 1.5 seconds, a warning is issued.

Versions of that algorithm were programmed for use in simulations and for trial runs in the ACC-with-braking car. Since there was not enough computing power to do both ACC and collision-warning in the ACC-with-braking car we developed a laptop computer version of the collision-warning algorithm and exercised it briefly during freeway driving. The results of this exercise showed that this particular implementation was impractical for this use because of excessive false alarms due to sensor anomalies.

Kinematic Analysis Employed in Evaluation

The NHTSA algorithm was originally analyzed using reasoning based upon trajectories in the range vs. range-rate diagram. A warning algorithm was produced and a version of the algorithm was sent to NHTSA. See Appendix F for a copy of these results.

However, later developments indicated that a conceptually simpler approach is viable. This approach is based upon the road-fixed variables V and Vp and $\dot{V}$ and $\dot{Vp}$ illustrated in Figure 1 near the beginning of this report. In addition the relative variables $\dot{R}$ and $\ddot{R}$ are used also. (Recall that $\dot{R}$ =Vp - V and $\ddot{R} = \dot{Vp} - \dot{V}$. Our Kalman filter approach provides estimates of R, $\dot{R}$, V, $\dot{V}$ and $\dot{Vp}$ in a form suitable for use in deciding whether to warn.)

The analysis logically depends upon whether the preceding vehicle is stopped or will reach a stop before the subject vehicle would reach a stop. Velocity diagrams such as the one shown in Figure 48 are convenient to use in deriving the basic relationships employed in the version of the NHTSA algorithm used to process the ICC FOT and FOCAS driving data.

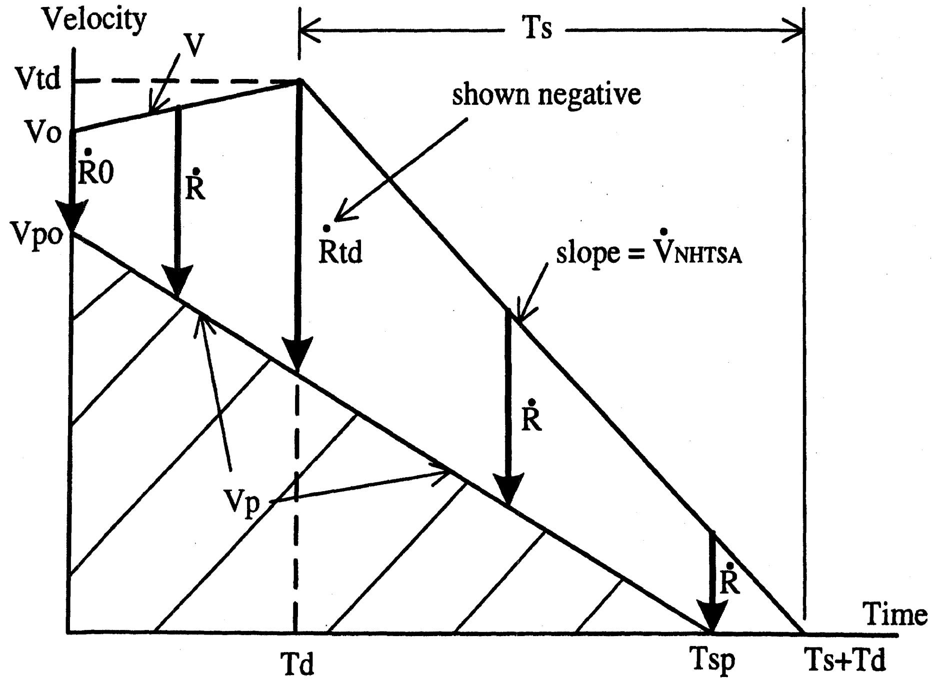


Figure 48. Velocity diagram for Ts+Td > Tsp

The basic idea behind the analysis shown in Figure 48 is simply that the change in range ΔR needed for this case is equal to the integral of $\dot{R}$ from $t = 0$ to $t = Ts + Td$. In this case (where straight lines represent periods of constant acceleration) ΔR is readily computed (using formulas for the areas of triangles and trapezoids), viz.,

$$\Delta R = -\frac{Vpo \cdot Tsp}{2} + (\frac{Vo + Vtd}{2}) \cdot Td + \frac{Vtd \cdot Ts}{2} \qquad (5.6)$$

where: $Tsp = -\frac{Vpo}{\dot{V}po}$ for $\dot{V}p0 < 0$, $Ts = \frac{Vtd}{-\dot{V}nhtsa}$, and $Vtd = Vo + \dot{V}o \cdot Td$

(Note: $-\frac{Vpo \cdot Tsp}{2}$ in equation 5.6 is the shaded triangle area under the Vp time history, $(\frac{Vo + Vtd}{2}) \cdot Td + \frac{Vtd \cdot Ts}{2}$ in equation 5.6 is the area under the V time history.)

There are a number of possible arrangements of Vo, Vpo, $\dot{V}o$ and $\dot{V}po$ that can occur. Analyses of these cases have been performed and they have been accounted for in the computer code attached in Appendix F.

In general, a warning is given if the existing range, Ro, is less than ΔR plus a minimum range factor as needed for accomplishing the emergency crash-avoidance maneuver selected by NHTSA. This means the warning is issued if Ro < ΔR +Rmin

Figure 49 illustrates a different type of situation in which $\dot{R}$ reaches zero before either vehicle reaches a stop.

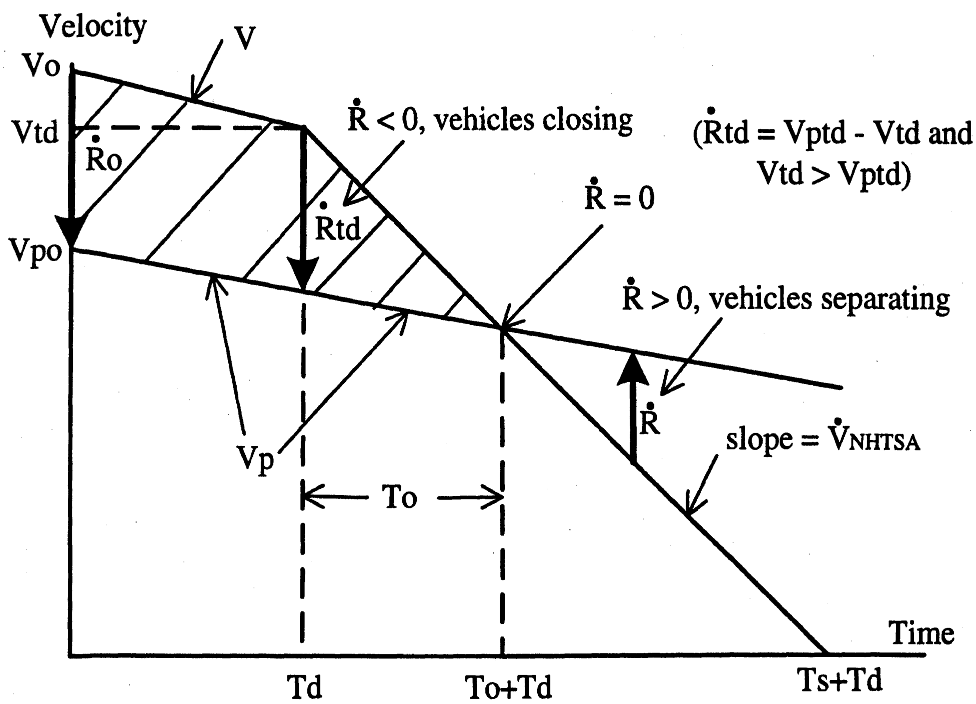


Figure 49. Diagram for Tsp > Ts+Td and 0 < To < Ts

In this case, the shaded area represents ΔR which is the integral of $\dot{R}$ from $t = 0$ to $t = To + Td$. The result of this integration is as follows:

$$\Delta R = -\left(\frac{\dot{R}o + \dot{R}td}{2}\right) \cdot Td - \frac{\dot{R}td \cdot To}{2} \tag{5.7}$$

where: $\dot{R}td = \dot{R}o + Td \cdot \ddot{R}o$,

$To = -\frac{\dot{R}td}{\ddot{R}td}$, given that $\ddot{R}o = \dot{V}po - \dot{V}o$ and $\ddot{R}td = \dot{V}po - \dot{V}nhtsa$, respectively.

As in the first case, there are a number of possible arrangements of Vo, Vpo, $\dot{V}o$ and $\dot{V}po$ to consider. These are accounted for in the attached computer code given in Appendix F.

The following list provides a rough outline of the operations programmed in the computer code for the algorithm.

1. Given the following parameters: Td = 1.5s, $\dot{V}nhtsa$ =-0.75 g, and Rmin = 7 ft. (2 m)
2. At each time step, read $Ro, \dot{R}o, Vo, \dot{V}o, \dot{V}po$ and any glitch messages from the Kalman filter operation on the data from the sensors.
3. Calculate condition variables
4. $\Delta R = 0$ (warning off)
5. $Vpo = Vo + \dot{R}o$
6. $\ddot{R}o = \dot{V}po - \dot{V}o$
7. $\dot{R}td = \dot{R}o + Td \cdot \ddot{R}o$
8. If $\dot{R}td \geq 0$ and $\dot{R}o \geq 0$, then go to step 4
9. If glitches are present, then go to step 4
10. $Vtd = Vo + \dot{V}o \cdot Td$
11. $Ts = \dfrac{Vtd}{-\dot{V}nhtsa}$
12. Tnhtsa = Td + Ts
13. $\Delta Rnhtsa = (\dfrac{Vo + Vtd}{2}) \cdot Td + \dfrac{Vtd \cdot Ts}{2}$
14. Calculate the needed (desired) range ΔR
15. If Vpo <= 0, then ΔR = ΔRnhtsa
16. If $\dot{V}po \geq 0$, then Tsp = 50, otherwise $Tsp = -\dfrac{Vpo}{\dot{V}po}$
17. If Tsp <= Tnhtsa, then
18. $\Delta R = \Delta Rnhtsa - \dfrac{Vo \cdot Tsp}{2}$, otherwise (Tsp >Tnhtsa)
19. If $\dot{R}td > 0$ and $\dot{R}o < 0$, then $To = -\dfrac{\dot{R}o}{\ddot{R}o}$ and $\Delta R = -\dfrac{\dot{R}o \cdot To}{2}$, otherwise
20. $\ddot{R}td = \dot{V}po - \dot{V}nhtsa$ and $To = -\dfrac{\dot{R}td}{\ddot{R}td}$ and $\Delta R = -\left[(\dfrac{\dot{R}o + \dot{R}td}{2}) \cdot Td + \dfrac{\dot{R}td \cdot To}{2}\right]$
21. Calculate warn value
22. If Ro > ΔR + Rmin, then warn = 0, otherwise warn = 1
23. Check for spurious, isolated warning. If warn has been 1 for at least 3 time steps, issue a warning, otherwise do not issue a warning.

24. Go to the next time step

5.3.2.2 Simulation Analysis of NHTSA Crash-Warning System

A new simulation program was developed during year 5 for analyzing crash-warning systems under various driving scenarios. A crash-warning model was developed, and it was incorporated into Simulink™. The purpose of the simulation was to provide a tool for examining the response of the proposed crash-warning system in typical headway conflicts which might be expected while driving. This tool was used to estimate the predictability and robustness of proposed crash-warning systems.

The crash-warning system's logic and computational flow is depicted in Figure 50.

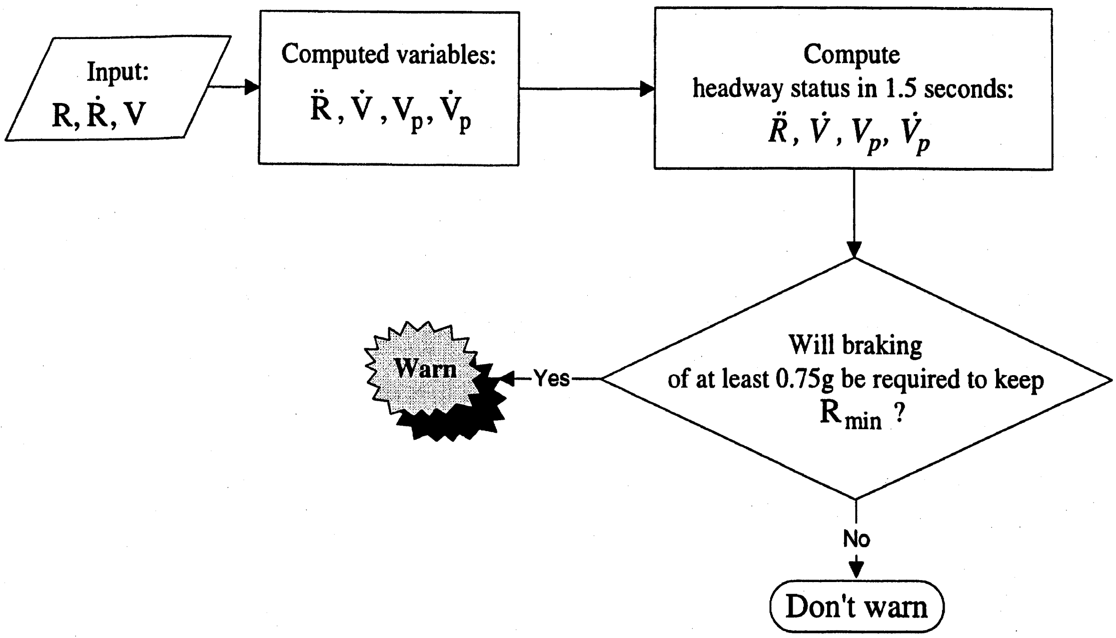


Figure 50. Crash-warning system logic and computational flow

The technique used to implement this crash-warning philosophy involved what we call the *now trajectory*, and the *crash-avoidance trajectory*. At each computational time-step, the first trajectory (the "now" trajectory) takes into account the current information about the headway situation, and it is "drawn" in the range versus range-rate space as the estimated projected trace. The second trajectory (the crash-avoidance trajectory) is a constant-deceleration parabola which intersects the range axis at the minimum prescribed range (7 ft in this case); this trajectory is also "drawn" in the same phase space. If these two trajectories do not intersect, it means that according to the model no risk of crash exists, hence no warning is issued. However, if the trajectories do intersect, it means that at some point in the future we predict that the driver will have to brake at a deceleration level of 0.75 g so as not to violate the minimum range boundary. The algorithm then computes the time it will take to reach that intersection point, and if it is less than 1.5 seconds — a warning is issued. This process repeats itself at each time step, so that the headway situation with the now trajectory and crash-avoidance trajectory are continuously being re-evaluated at the cycle rate of the warning system.

5.3.3 Results

The Simulink™ model was exercised to simulate several headway-conflict scenarios. Certain decisions were made in the development of the model that pertain to the strategies used in controlling the duration and termination of the warning signal (e.g., once triggered, the signal is kept active as long as $\dot{R}<0$). These strategies and how they affect the simulation results will be discussed later in conjunction with the relevant outputs.

5.3.3.1 Low Deceleration of Lead Vehicle From Following

In the context of this report, low, medium, or high as applied to deceleration should be regarded as relative descriptors. Since the follower applies 0.75 g braking when a warning is initiated, one may consider braking of 0.2 g by the lead vehicle as low deceleration. The particular example simulated here involves a braking application of 0.23 g by the lead vehicle from an initial situation where the second vehicle was following at a constant speed, 160 ft behind.

The speed-profile response and the range versus range-rate phase plane simulation results are shown in Figure 51 and Figure 52.

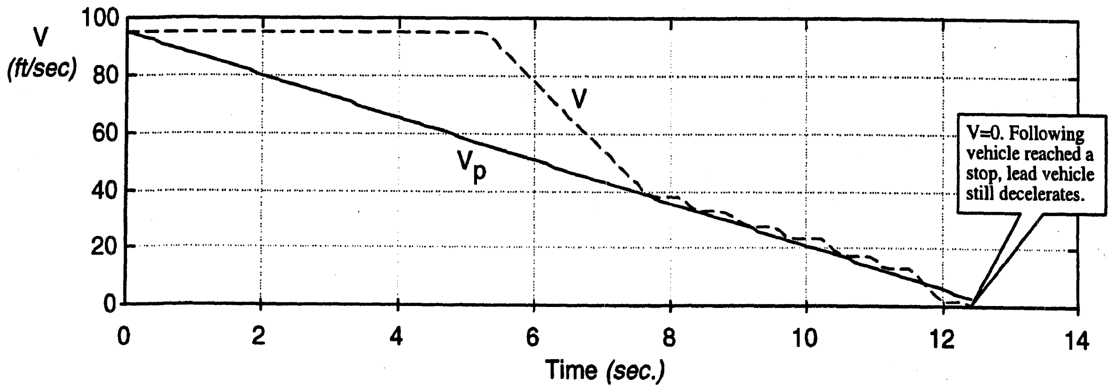


Figure 51. Speed profiles of lead and follower vehicles

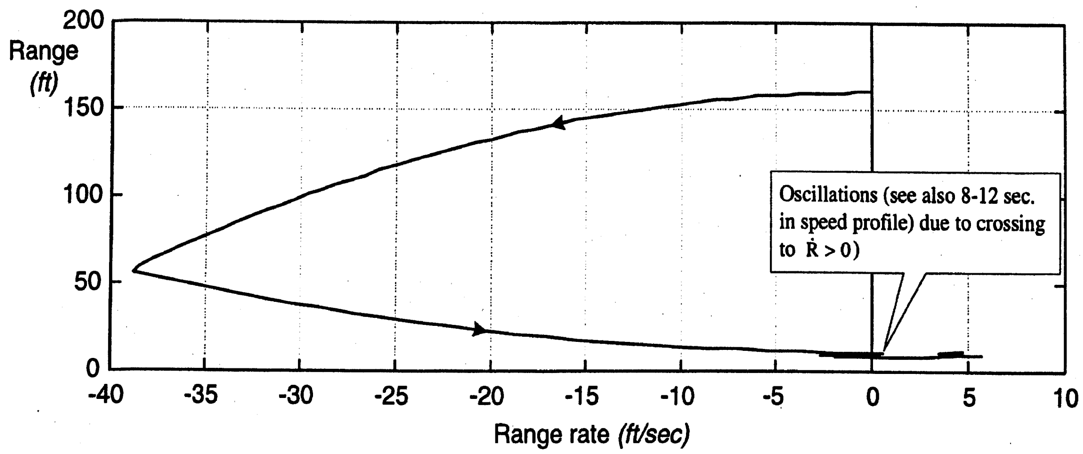


Figure 52. Phase plane simulation output

At first, the speed of both vehicles is 95 ft/s, with the follower at a range of 160 ft behind the lead vehicle. At t = 0 the lead vehicle starts to decelerate at a rate of 0.23 g. It is not until approximately t = 5.2 s, when the range drops to 55 ft, that the follower starts to react by a deceleration of 0.75g. The warning signal and the ensued deceleration are shown in Figure 53. Note the 1.5 s delay in deceleration after the warning is initiated. As the follower slows down and the range-rate becomes positive (see also Figure 54), the warning signal is turned off and the follower now keeps a constant speed. That causes the range-rate to become negative again so that the warning is initiated, braking ensues, and the cycle repeats.

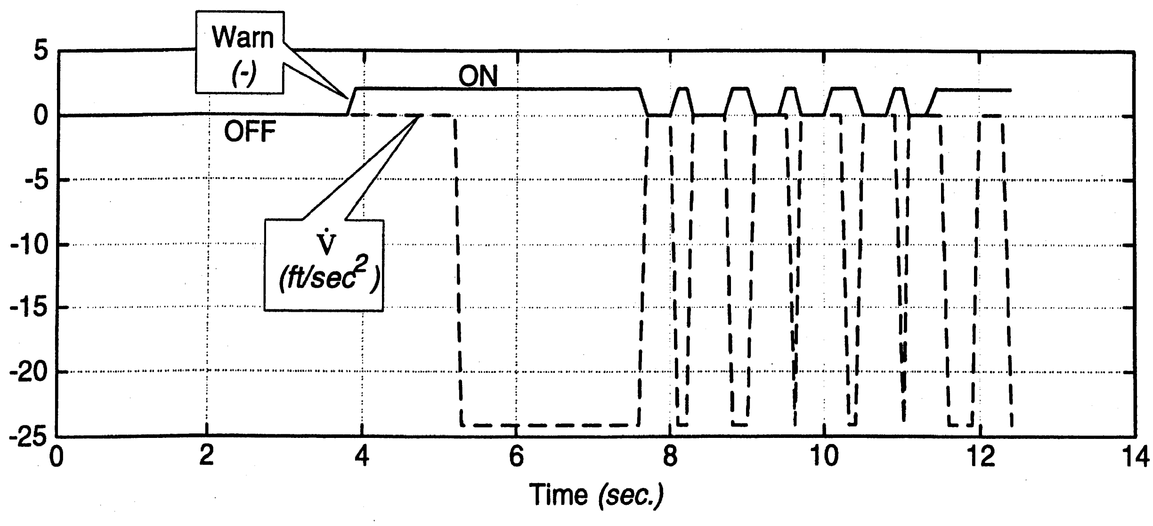


Figure 53. Warning signal and ensued deceleration

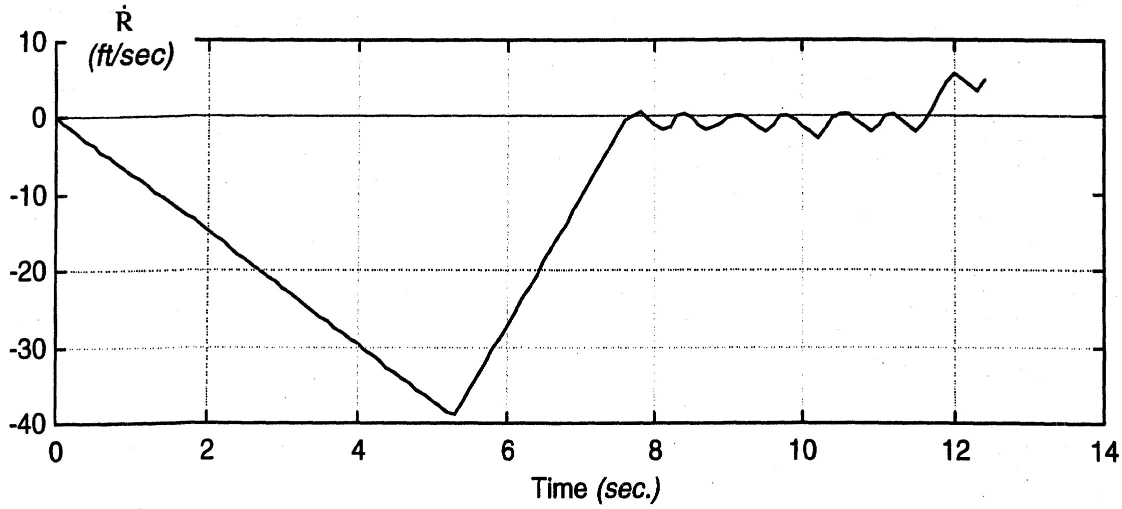


Figure 54. Range-rate profile

5.3.3.2 Medium Deceleration of Lead Vehicle From Following

This simulation involves a braking application of 0.5 g by the lead vehicle from an initial situation where the second vehicle was following at a constant speed, 160 ft behind (same initial conditions as the previous example). The speed-profile response and the range versus range-rate phase plane simulation results are shown in Figure 55 and Figure 56. The time history of the simulated warning signal and the ensued deceleration is shown in Figure 57.

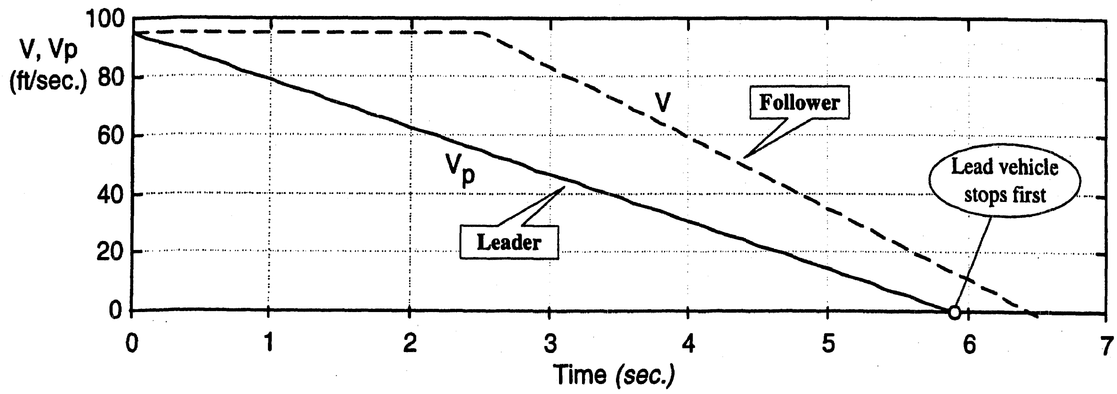


Figure 55. Speed profiles of lead and follower vehicles

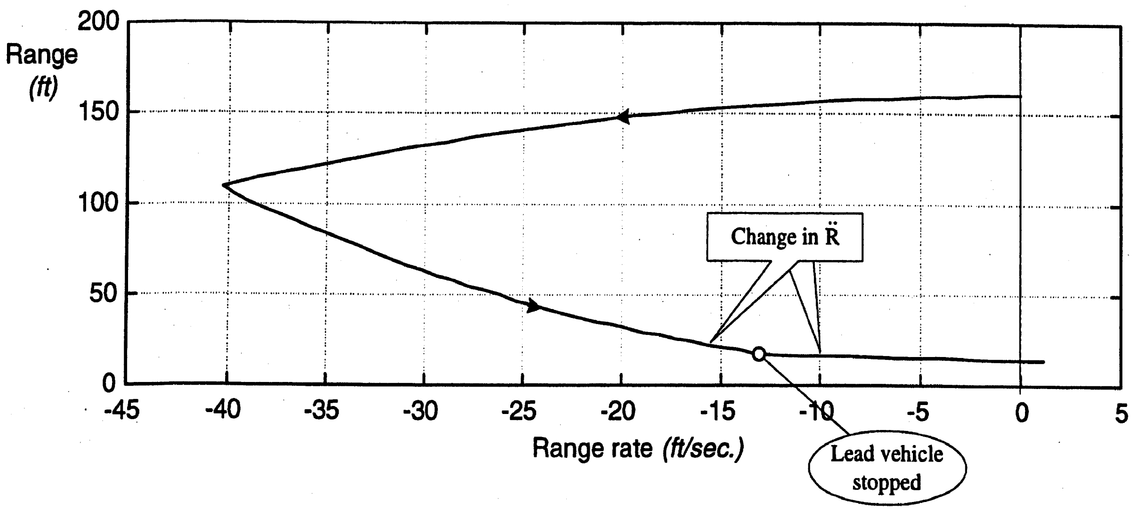


Figure 56. Phase plane simulation output

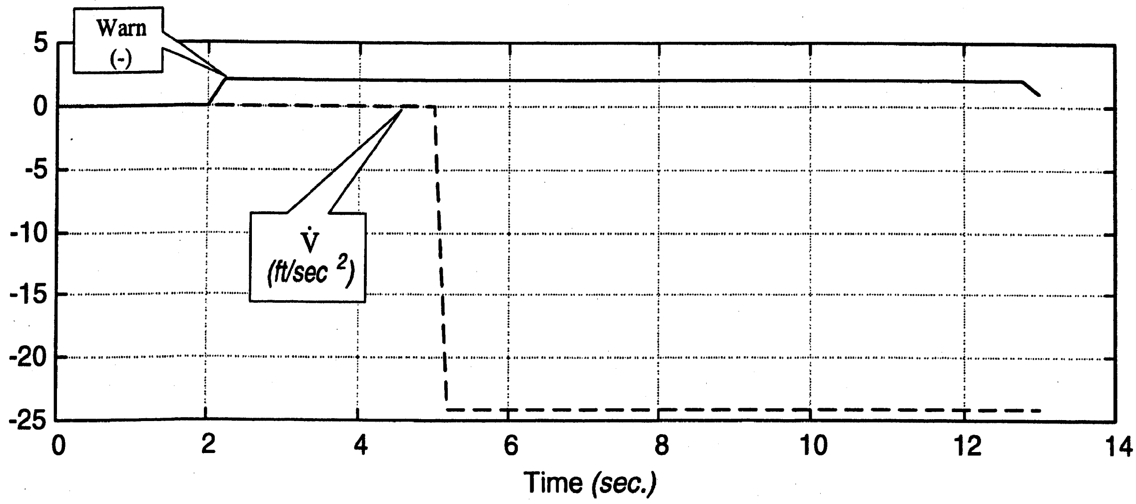


Figure 57. Warning signal and ensuing deceleration

Both this and the preceding examples involve the uninterrupted warning algorithm. In spite of the fact that the lead vehicle does reach a full stop in this example, the warning has already been triggered and the brakes are applied.

5.3.3.3 Approaching a Stopped Vehicle From a Long Distance

In this example the simulated vehicle is driven at 60 mph (88 ft/sec), and it approaches a preceding vehicle that is stopped. The initial range between the vehicles is 350 ft. The speed-profile response and the range versus range-rate phase plane simulation results are shown in Figure 58 and Figure 59.

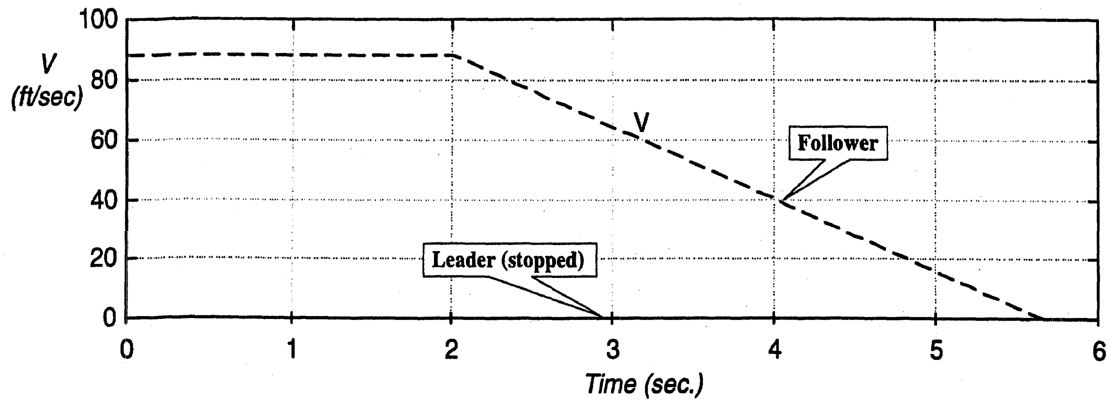


Figure 58. Speed profiles of preceding and follower vehicles

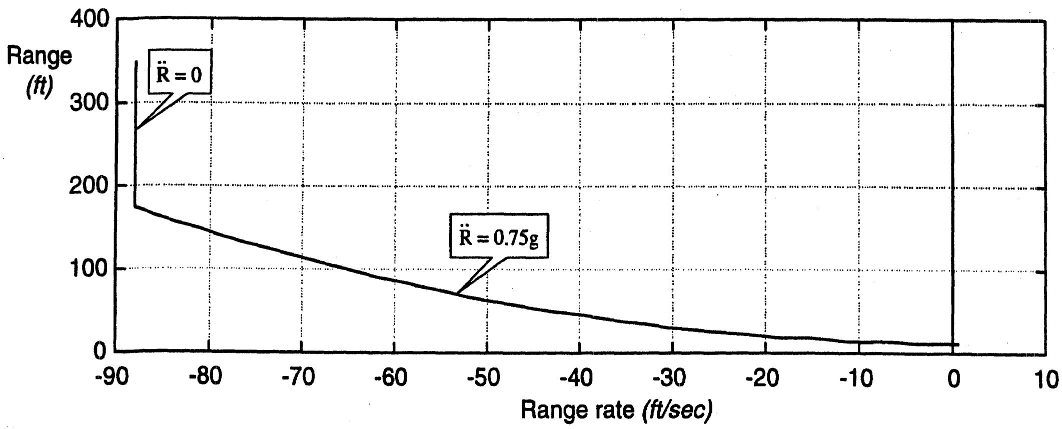


Figure 59. Phase plane simulation output

The slope in the range-rate plot in Figure 60 corresponds to $\ddot{R} = 0.75g = -\ddot{V}_n$. Since the preceding vehicle is stopped ($\dot{V}_p = 0$), it does not contribute to $\ddot{R}$.

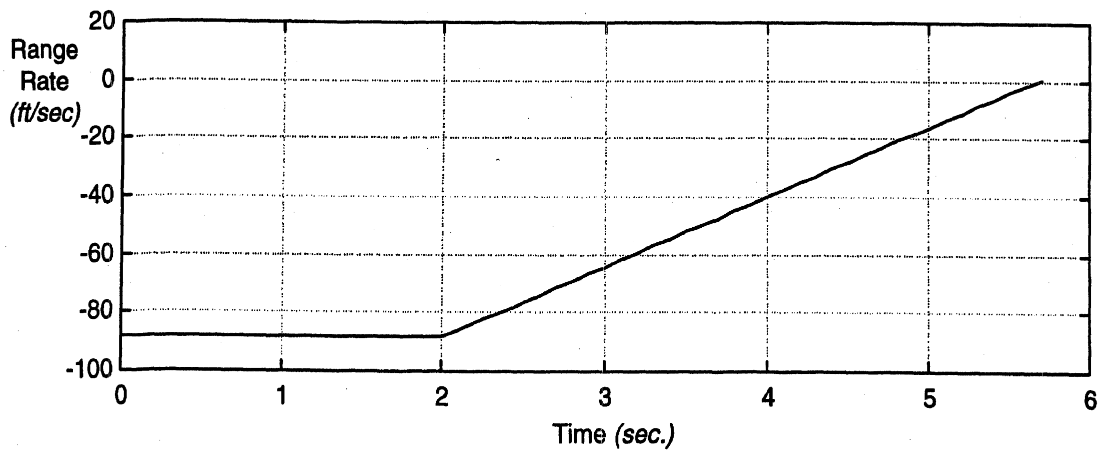


Figure 60. Range-rate profile

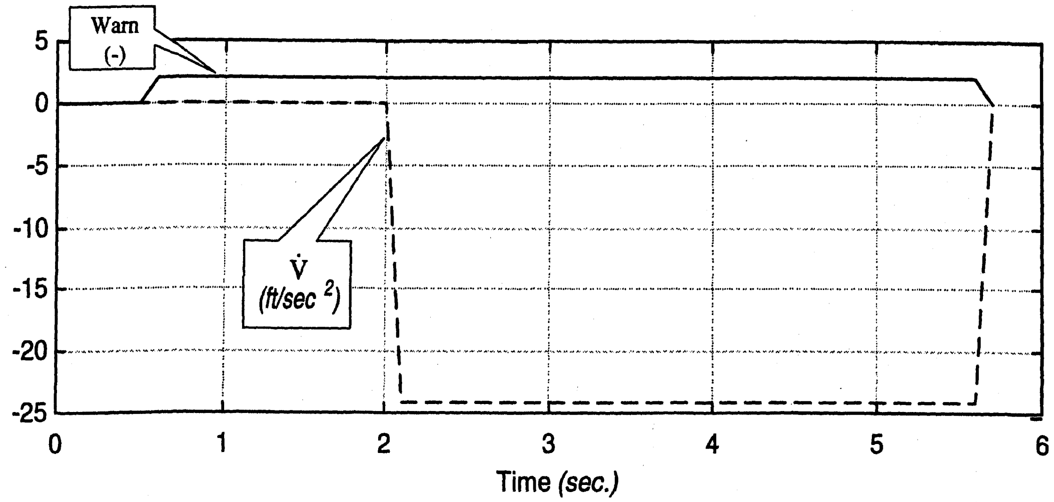


Figure 61. Warning signal and ensued deceleration

5.3.4 Findings and Recommendations

The NHTSA FCW concept was explored in great detail in this work. Earlier work in FOCAS developed an algorithm based on analysis of the range and range-rate space. This approach was based on both fixed road coordinates along and the relative coordinates of range-rate and its derivative. Derivation of equations to handle all the possible relationships between the leading and following vehicle was greatly reduced using velocity diagrams. This work resulted in a set of logical steps to test the NHTSA FCW concept and an actual coded algorithm.

5.4 Evaluation of FCW Systems

5.4.1 Research Activities

UMTRI also undertook to support NHTSA in studies that sought to analyze the performance of collision-warning algorithms using archival data from the ICC FOT. Specifically, other NHTSA contractors in using data from the ICC FOT, were concerned with data filtering and/or smoothing issues as needed for predicting the performance of the NHTSA algorithm. Research activities for the 5th year included the development of methods for using the ICC FOT data to aid in evaluating the expected performance of proposed FCW systems. These methods were applied by UMTRI in evaluating the Ttc and Vcdot warning algorithms. In addition, a new and different approach was developed for implementing the NHTSA algorithm. This new version of the NHTSA algorithm was exercised using data from the ICC FOT.

5.4.1.1 Analytical descriptions of the three algorithms studied

NHTSA emergency braking warning algorithm

Refer to equation 5.6 and 5.7 in section 5.3. The quantity ΔR needed for driver reaction time followed by emergency braking is computed. If R is less than ΔR a warning is issued.

Time-To-Impact Warning Algorithm

In addition to the NHTSA design that was based on deceleration of the lead vehicle ($\dot{V}_p$), two designs that did not use $\dot{V}_p$ were configured.

The simplest of the three designs is based on time-to-impact calculations:

$$TTI = \begin{cases} \dfrac{R}{-\dot{R}} & \text{for } \dot{R} < 0 \\ \text{Not Valid} & \end{cases} \tag{5.8}$$

When TTI is valid, and when its value is below a selected threshold level, a warning is issued.

Desired-Deceleration Warning Algorithm

The third design (called "Vcdot") is based on the following equation taken from the report addressing driver response delays [11]:

$$\dot{V}_c = \left(V/R\right)\left[\dot{R} + \left(\frac{R - T_h \cdot V}{T_e}\right)\right] \qquad \text{for } \dot{R} < 0 \tag{5.9}$$

In this design, the computed $\dot{V}_c$ is compared to a threshold value. If it is less than the threshold, the warning is issued.

5.4.2 Analysis Methodology

5.4.2.1 Special Data-Processing Techniques

Crash warning systems are very quick to respond—all they have to do is to activate an alarm. As such, some system designs may be very sensitive to the fidelity of the data upon which they rely.

Three variables form the foundation for the various crash-warning algorithms: range, range-rate, and velocity. The data used in FOCAS to evaluate such algorithms originated from the ICC FOT and from FOCAS highway testing with lay drivers. In both cases, the sources of these variables were the prototype IR sensors provided by ADC and the speed signal from the Chrysler Concorde. Since the quality of these signals was insufficient to be used directly in a warning algorithm because too many false alarms were generated, a Kalman filter approach was developed. Figure 62 shows the data flow used in the FOCAS project for both the ACC and FCW systems. An important distinction is made between the actual range, range-rate, and velocity of the vehicle and the measured range, range-rate and velocity (denoted as $\hat{R}$, $\hat{R}$dot, and $\hat{V}$ in Figure 62). In a perfect world these variables would agree in both magnitude and phase, but undoubtedly there will be differences. For the ACC application, errors in the measured variables had little effect on the performance of the system since the vehicle itself acted like a large damper incapable of responding quickly to command errors resulting from erroneous measured values. However, as mentioned before, FCW applications only involve sounding an alarm and thus are much more sensitive to erroneous data—after all, in FCW applications, time is of the essence, so promptness of an alarm is critical. To remedy mistakes in the three critical measured variables and to provide accurate estimates of their derivatives, a Kalman filter was added to the data flow as shown conceptually in Figure 62. Appendix G lists the computer code of the Kalman filter discussed in the following pages. That appendix includes also a discussion about how certain data anomalies (glitches) were handled.

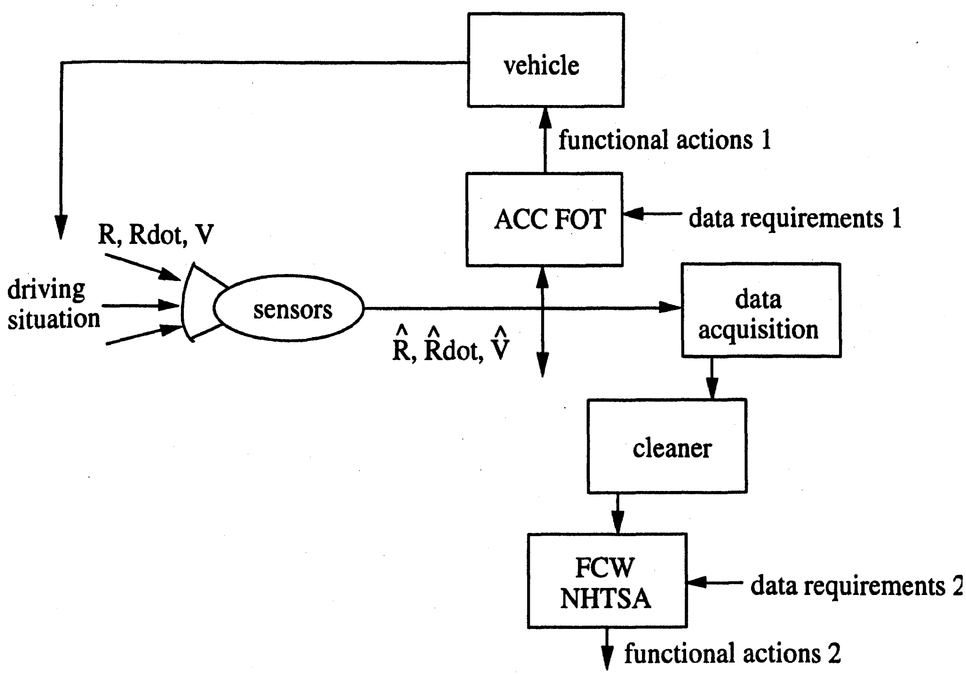


Figure 62. Data flow for ACC and FCW systems in FOCAS

Methodology

The approach we used to resolve data-quality issues is based on the Kalman filter theory. From [13], simply put, "the Kalman filter is used to estimate, on the basis of noisy measurements, the value of the state variables of a system subject to stochastic input disturbances."

A dynamic model of the system was developed based on the variables illustrated in Figure 63.

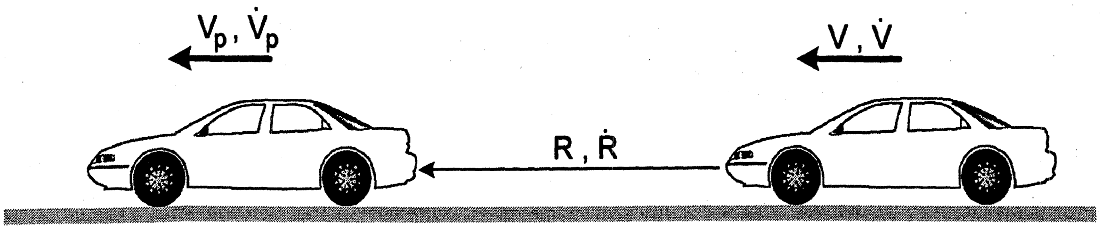


Figure 63. Variables of the headway model

Given the standard format of the state-space linear model given in equation 5.10, the rest of the model elements are defined below.

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{5.10}$$

$$x = \begin{Bmatrix} R \\ \dot{R} \\ V \\ \dot{V} \\ \dot{V}_p \end{Bmatrix}, \text{ and } A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5.11}$$

$$y = \begin{Bmatrix} R \\ \dot{R} \\ V \end{Bmatrix}, \text{ and } C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{5.12}$$

The matrices B and D are zero, since there is no input other than the value of the state variables (x) that affect the output (y). We do not have information about the driving forces of the vehicle in this analysis, hence the vector, u, in equation 5.10 is not included. It is expected that this lack of knowledge will cause delays in the Kalman filter estimation of the vehicle's acceleration during rapid speed changes [14]. In this application of the Kalman filter, the intention is simply to use existing measurements and a dynamic model to estimate the "true" value of the output. Also, no white noise is added here, since it is assumed that such noise is already embedded in the measurements.

At each time point (n) we extrapolate to the next (n+1), to predict the "future" value of the state variables. Also, based on the previous step's prediction, we predict what measurements we will get at the current time step. The discrete-time format of the state-space equations in 5.13 is given by:

$$\begin{aligned} \bar{x}_{n+1} &= \Phi \cdot \hat{x}_n \\ \hat{y}_n &= C \cdot \bar{x}_n \end{aligned} \tag{5.13}$$

Where $\bar{x}_{n+1}$ is the extrapolated future value of the state variables at the next time step, $\hat{x}_n$ is the output of the Kalman filter at the end of the current time step (the best estimate of the state variables), and Φ is called the *transition* matrix. $\hat{y}_n$ is a *model-based prediction* of the measurements that we will get (in the current time step), based on the extrapolated value of the state variables (computed in the previous time step). With a time step of Δt, the transition matrix is given by:

$$\Phi = \begin{bmatrix} 1 & \Delta t & 0 & -\Delta t^2/2 & \Delta t^2/2 \\ 0 & 1 & 0 & -\Delta t & \Delta t \\ 0 & 0 & 1 & \Delta t & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.14}$$

(Equation (5.14) assumes that $\dot{V}$ and $\dot{V}_p$ are practically constant during each time step.)

Once measurements are taken ($\tilde{y}_n$), the error between the model-based prediction and the actual measurements is calculated. This error is multiplied by what is called the *Kalman feedback gain.* The result is combined with the extrapolated values of the state variables to provide a new, best estimate for the current step's "true" value of state variables. This *predictive-corrective* process is illustrated in Figure 64.

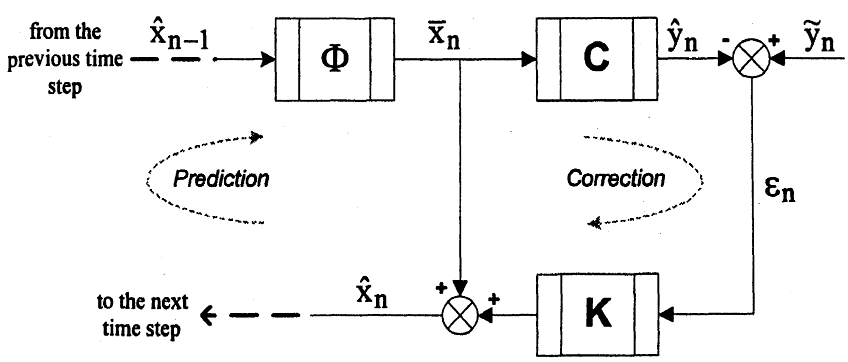


Figure 64. Kalman predictive-corrective process

Using equation (5.13) and the process depicted in Figure 64, the first two Kalman equations can now be written:

$$\bar{x}_n = \Phi \cdot \hat{x}_{n-1} \tag{5.15}$$

$$\hat{x}_n = \bar{x}_n + K_n(\tilde{y}_n - C \cdot \bar{x}_n) \tag{5.16}$$

In the above equation (5.16), the Kalman feedback gain is denoted as K_n, indicating a matrix-variable that is being updated at each time step. This adaptive process is convenient to use in simulations, and/or when there is no firm knowledge of the covariance matrices (see discussion below) that describe the statistical fidelity of the model and the measurements. It should be noted that, for many real-time dynamic systems, the Kalman gain typically adapts and reaches steady-state in a relatively short period. For such systems the Kalman filter gain can be calculated off-line for specific situations, stored as a lookup table, and used as a constant-value gain for the various situations.

The Kalman feedback gain is given by equation (5.17) below, which is based on the solution of the matrix Riccati equation [17].

$$K_n = \frac{P_n \cdot C^T}{C \cdot P_n \cdot C^T + R} \tag{5.17}$$

Two covariance matrices are included in equation (16) to provide the statistical quantifiers of the stochastic control problem being evaluated. Without getting into detailed statistical analysis, the general structure of the covariance matrices can be described by equations (5.18) and (5.19) below (from [18]). SVi and MVi in these equations stand for the ith state variable and the ith measured variable respectively. Both matrices are square, where P is of the same length as x, and R is of the same length as y. For obvious reasons, the P and R matrices are called *state-variables covariance matrix* and *measurements covariance matrix*, respectively. There is no feedback from the state equations to the covariance equations.

$$P = \begin{bmatrix} \text{mean square error of SV1} & \text{error cross - correlation between SV1 and SV2} & \cdots & \text{error cross - correlation between SVi and SVj} & \cdots \\ \text{error cross - correlation between SV2 and SV1} & \text{mean square error of SV2} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \text{error cross - correlation between SVj and SVi} & \cdots & \cdots & \text{mean square error of SVi} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \tag{5.18}$$

$$R = \begin{bmatrix} \text{mean square error of MV1} & \text{error cross - correlation between MV1 and MV2} & \text{error cross - correlation between MVi and MVj} \\ \text{error cross - correlation between MV2 and MV1} & \text{mean square error of MV2} & \cdots \\ \text{error cross - correlation between MVj and MVi} & \cdots & \text{mean square error of MVi} \end{bmatrix} \tag{5.19}$$

In the system studied here, the following assumptions were made:

- measurement errors are uncorrelated and independent of each other
- the mean square error of the measurements is part of the measuring devices and therefore it does not change during the test/simulation
- matrix P is going to be a full 5x5 matrix (for our system, with 5 state variables) which is too complex to establish a priori, and we have no estimate for the errors associated with two of the variables ($\dot{V}$ and $\dot{V}_p$)
- as an initial guess, P will be a 5x5 identity matrix, and Kalman's provision for updating the matrix will reach its steady state soon enough
- errors and noise are random (white noise)

From the technical information of the sensors, the mean error for range is 0.45 m (1.5 ft, square mean of 2.25 ft^2), and the mean error for range-rate is 1.5 km/h (1.375 ft/sec, square mean of 1.9 $(ft/sec)^2$). It was assumed that the vehicle's speed signal has a 1 mph

(1.6 km/h, 1.47 ft/sec, square mean of 2.15 $(ft/sec)^2$) accuracy. According to the above information, the covariance matrices are written (again, for P it's only an initial guess):

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.20}$$

$$R = \begin{bmatrix} 2.25 & 0 & 0 \\ 0 & 1.9 & 0 \\ 0 & 0 & 2.15 \end{bmatrix} \tag{5.21}$$

Kalman's equation for the discrete-time update of the state-variables covariance matrix is given by the following equation (5.22). The matrix Q in this equation is the *noise covariance matrix*, and it provides weighting of the noise which affects the stochastic nature of the system as a whole, and that of the individual variables. Because the noise is assumed to equally affect all the variables, the value of Q used here was the same as P in equation (5.20). The scalar λ is a tuning factor that is established via trial-and-error process (using a data sample) to provide a good fit. The chosen value for λ is 0.2. In this model both λ and Q remain constant throughout the remainder of the tests.

$$P_n = \Phi \cdot \overline{P}_{n-1} \cdot \Phi^T + Q \cdot \lambda \tag{5.22}$$

where $\overline{P}_{n-1}$ is the extrapolated covariance matrix, calculated at the end of the last step. Equation (5.23) provides the expression for calculating $\overline{P}_n$ (done at the end of step n):

$$\overline{P}_n = [I - K_n \cdot C] \cdot P_n \tag{5.23}$$

A diagram showing the actual program flow of the discrete Kalman filter used in this study is provided in Figure 65.

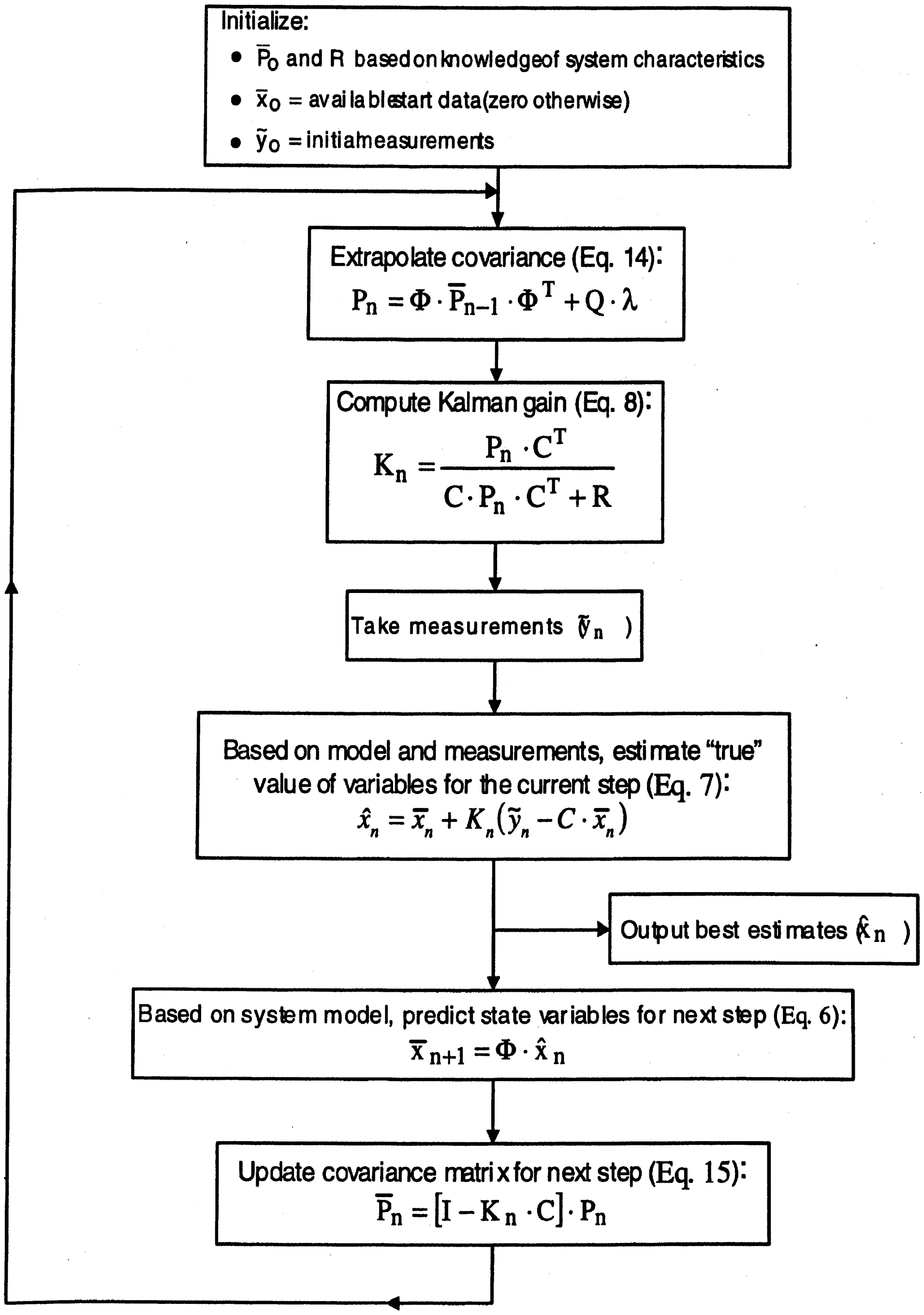


Figure 65. Kalman filter program flow

5.4.3 Results

5.4.3.1 Braking Events

In year five, three collision-warning algorithms were exercised using the FOT and FOCAS data sets. This section of the report presents the results. The approach for testing the algorithms was not to use all the data contained in these data sets, but to be selective and use only a subset of the naturalistic driving archive. Based on previous work, which studied the FOT data set to identify driver response delays [11], a set of events was identified in the FOT and FOCAS data sets that were likely to represent driving situations with high levels of conflict and hence candidates for a collision-warning algorithm. The discussion below begins with the rules used to identify these braking events. This is followed by results that characterize these events in terms of statistics, distributions and sample time history plots. The last section presents the results of the collision-warning analysis.

Braking Event Analysis

In previous work the ICC FOT data were examined electronically to gather information on driver behavior when the preceding vehicle was braking [11]. The goal of this analysis, was to identify and measure the delay, latency or wait time of driver braking when prompted by a preceding vehicle that is also braking. To accomplish this, a set of procedures was developed that identified the times when significant decelerations occurred in both the preceding and ACC vehicles.[1] The details of these procedures are discussed in [11].

In all the FOT data, which covered 114,000 miles of driving by 108 different drivers, the braking analysis procedures found 303 hard braking cases during manual driving and 67 cases where the driver intervened, by braking, on the ACC system. A similar analysis was done on the FOCAS data set of 24 accompanied drivers. In this set, the procedures identified 18 manual events and 9 ACC cases. All of these results have been compiled into brake event tables. Shown below, in Table 12, are the FOCAS results. The FOT results are given Appendix H. These tables contain 29 fields of data that identify and help characterize the forward conflict and the level and severity of the brake event. Three of these fields, labeled NHTSA, Ttc, and VcDot, show the collision-warning results, which are discussed in more detail in the next section. All 29 fields are described in Table 13.

[1] The data set for the FOT vehicle included a brake-switch signal indicating driver braking. However, there is no signal for the preceding vehicle so analysis of the velocity and acceleration time histories were necessary to determine times of likely braking by the driver of the preceding vehicle. Furthermore, since the deceleration profiles and their correlation with brake applications showed large variations (i.e., drivers can be on the brake without causing much deceleration), a similar analysis was done on the FOT vehicle as opposed to just using the brake-pedal signal.

Table 12. Twenty-seven brake events from the FOCAS data set.

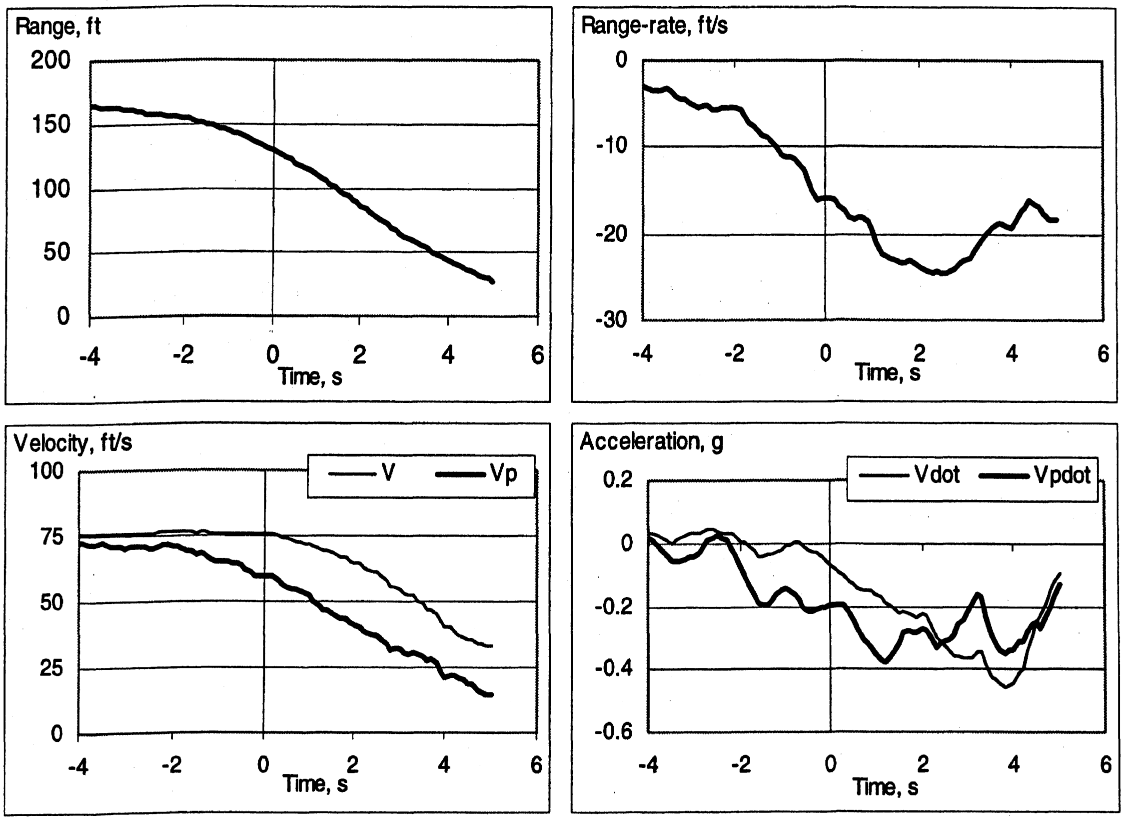
				Preceding Vehicle "Brake On"						Acc Vehicle Brake On						Event Minimums						Δ T & V		Warnings			Severity	
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	13	563	1	47	-3	78	75	0.6	15	46	-3	78	74	0.6	14	-0.20	-0.23	29	-7	0.4	4	3.3	-14	0	1	1	-0.05	-0.16
Man	9	555	2	125	5	92	96	1.4	50	103	-10	90	80	1.1	10	-0.22	-0.27	84	-12	1.1	8	2.6	-12	0	1	0	-0.05	-0.20
Man	9	555	3	134	-5	81	77	1.6	29	134	-5	81	77	1.6	29	-0.14	-0.16	94	-8	1.5	13	8.6	-25	0	0	0	-0.10	-0.13
Man	13	563	4	22	-5	84	79	0.3	5	24	-4	84	80	0.3	5	-0.21	-0.20	18	-5	0.2	4	2.4	-10	0	1	1	-0.10	-0.10
Man	24	592	5	94	0	107	107	0.9	50	90	-2	106	104	0.8	43	-0.15	-0.14	83	-3	0.8	27	2.9	-9	0	0	0	-0.05	-0.09
Man	14	564	6	76	1	83	84	0.9	50	74	-1	82	81	0.9	50	-0.17	-0.29	59	-6	0.8	10	3.5	-13	0	1	0	-0.05	-0.18
Man	21	585	7	79	-2	103	100	0.8	35	75	-4	101	97	0.7	18	-0.14	-0.17	67	-6	0.7	12	1.7	-7	0	0	0	-0.10	-0.11
Man	12	561	8	56	-4	88	84	0.6	16	54	-4	87	83	0.6	13	-0.23	-0.24	44	-6	0.6	7	2.9	-15	0	1	0	-0.15	-0.14
Man	19	581	9	86	-2	78	76	1.1	49	86	-2	78	76	1.1	50	-0.23	-0.29	71	-5	1.1	15	6.5	-30	0	0	0	-0.10	-0.21
Man	21	585	10	40	-1	97	95	0.4	28	41	-1	97	96	0.4	32	-0.22	-0.28	32	-4	0.4	8	2.7	-16	0	1	0	-0.10	-0.17
Man	19	581	11	71	-3	98	96	0.7	28	71	-3	98	95	0.7	25	-0.40	-0.34	41	-11	0.5	4	5.2	-34	0	1	1	-0.10	-0.27
Man	3	533	12	102	9	80	89	1.3	50	97	-2	79	78	1.2	50	-0.17	-0.31	81	-7	1.0	12	4.4	-11	0	0	0	-0.05	-0.21
Man	3	533	13	101	-7	106	99	1.0	14	100	-8	106	99	0.9	13	-0.21	-0.19	73	-9	0.8	9	3.9	-18	0	1	0	-0.10	-0.12
Man	3	533	14	209	-1	83	82	2.5	50	208	-1	82	81	2.5	50	-0.13	-0.15	203	-2	2.5	50	2.9	-9	0	0	0	-0.05	-0.08
Man	11	559	15	151	0	103	102	1.5	50	110	-16	101	85	1.1	7	-0.15	-0.23	86	-17	0.9	6	1.9	-8	0	1	1	-0.15	-0.20
Man	3	533	16	61	-3	100	97	0.6	23	58	-4	100	96	0.6	16	-0.13	-0.16	50	-6	0.5	9	4.3	-14	0	1	0	-0.05	-0.10
Man	14	564	17	124	2	80	81	1.6	50	116	-4	81	76	1.4	26	-0.20	-0.20	106	-7	1.4	16	4.3	-17	0	0	0	-0.05	-0.11
Man	16	569	18	67	0	89	88	0.8	50	66	-1	88	87	0.7	50	-0.29	-0.30	56	-5	0.7	11	3.0	-16	0	0	0	-0.05	-0.15
Acc	21	585	1	133	-8	105	96	1.3	16	123	-10	104	94	1.2	12	-0.15	-0.21	93	-13	1.0	8	2.5	-9	0	1	0	-0.05	-0.16
Acc	24	592	2	122	-2	95	93	1.3	50	115	-6	95	89	1.2	19	-0.13	-0.19	98	-10	1.1	10	2.3	-7	0	1	0	-0.05	-0.14
Acc	8	554	3	61	-1	86	86	0.7	50	62	-1	87	87	0.7	50	-0.23	-0.21	59	-6	0.7	12	3.5	-16	0	0	0	-0.05	-0.12
Acc	8	554	4	163	-3	104	101	1.6	50	152	-8	104	96	1.5	19	-0.17	-0.23	120	-12	1.3	10	2.9	-11	0	1	0	-0.05	-0.16
Acc	7	550	5	80	-6	82	76	1.0	14	68	-10	82	72	0.8	7	-0.28	-0.36	53	-13	0.8	5	1.4	-12	0	1	1	-0.05	-0.22
Acc	7	550	6	79	-3	89	85	0.9	23	77	-4	88	84	0.9	19	-0.20	-0.21	70	-6	0.8	11	3.0	-12	0	0	0	-0.05	-0.10
Acc	16	569	7	172	-3	88	85	2.0	50	170	-3	87	84	2.0	50	-0.30	-0.24	100	-8	1.9	15	20.2	-61	0	0	0	-0.10	-0.16
Acc	19	581	8	118	-6	101	95	1.2	20	112	-8	100	93	1.1	14	-0.21	-0.23	76	-13	0.9	6	4.7	-21	0	1	1	-0.05	-0.19
Acc	12	561	9	56	6	102	108	0.6	50	49	-3	102	99	0.5	16	-0.20	-0.18	36	-7	0.4	6	4.3	-19	0	1	1	-0.05	-0.16

Table 13. Field definitions of the brake event table

Category	Field	Description
Event Classification		Identification parameters
	Cntrl	Control mode: Man = manual control; ACC = adaptive cruise control
	Drv	Driver identification number
	Trip	Trip identification number
	#	Sort number
Preceding Vehicle Brake On		The instant in time when the preceding vehicle's acceleration dropped below -0.1 g
	R	Range, in ft, to the preceding vehicle at the Brake On time
	Rdot	Range-rate, in ft/s, to the preceding vehicle at the Brake On time
	V	Velocity, in ft/s, of the ACC vehicle at the Brake On time
	Vp	Velocity, in ft/s, of the preceding vehicle at the Brake On time
	Htm	Headway-time-margin, in s, to the preceding vehicle at the Brake On time
	Ttc	Time-to-collision, in s, to the preceding vehicle at the Brake On time
ACC Vehicle Brake On		The fields are identical to the preceding vehicle category but measured when the ACC driver depresses the brake pedal
Event Minimums		Minimum values for an event. (where an event starts 4 seconds before the ACC brake application and lasts until the ACC vehicle brake is released
	Vdot	ACC vehicle acceleration in g's
	Vpdot	Preceding vehicle acceleration in g's
	R	Range, in ft, to the preceding vehicle
	Rdot	Range-rate, in ft/s, to the preceding vehicle
	Htm	Headway-time-margin, in s, to preceding vehicle
	Ttc	Time-to-collision, in s, to preceding vehicle
ΔT and ΔV		Brake duration and velocity change of ACC vehicle
	ΔT	Duration, in s, of the ACC brake application
	ΔV	Change in velocity, in ft/s, of the ACC vehicle during the brake application
Warnings		Warning algorithms, 1=warning triggered
	NHTSA	The forward collision-warning algorithm (emergency)
	Ttc	The nervous passenger warning algorithm (time-to-collision)
	Vcdot	The back seat driver warning algorithm (expected deceleration)
Severity		Numerics designed to measure the severity of the events
	Const Ax	The constant acceleration needed for the ACC vehicle to avoid a crash if applied at the time of the brake application.
	Avoid Ax	The minimum acceleration needed to avoid a crash as calculated during the entire time of the event: AvoidAx=Vpdot-((Rdot)*(Rdot)/(2*R))

Results from FOT and FOCAS brake event tables

Although only the FOCAS brake event table is shown in the text, this discussion will present results from both the FOT and FOCAS event tables. Shown in Figure 66 are time history plots and the associated brake event values for FOT event 128. Time histories of range, range-rate, velocity, and acceleration are shown in the four views of the figure.



Preceding Vehicle Brake On						ACC Vehicle Brake On					
R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s
153	-6	77	70	2.0	24	131	-16	75	60	1.7	8

Event Minimums						ΔT & V		Warnings			Severity	
Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHTSA	Ttc	VcDot	Const Ax, g	Avoid Ax, g
-0.46	-0.38	27	-24	0.8	1	5.2	-43	1	1	1	-0.20	-0.45

Figure 66. Time history plots and associated brake event values for FOT event 128 (driver 93, trip 89)

The velocity and acceleration views show traces for both the ACC vehicle (V and Vdot) and the preceding vehicle (Vp and Vpdot), respectively. The time scale for the plots is adjusted such that zero time represents when the driver of the ACC vehicle applied the brakes—hence the start of the brake event. Positive time values reflect the entire duration of the brake event, while negative time values show a four second window prior to the brake event. (Note: in all the warning analysis results shown in the brake event tables, a four-second preview was used since it is conceivable that a collision-warning algorithm could be triggered before the ACC or preceding vehicle started to brake.)

In the data processing procedures, the preceding vehicle brake on time is based on an acceleration threshold of –0.1 g. In the example shown in Figure 66, the approximate time for the preceding vehicle braking event is 2.0 s prior to the ACC vehicle brake application time. The values of range, range-rate, velocity, etc., for this event are shown below the plots in the table under the field labeled Preceding Vehicle Brake On. By definition, the ACC vehicle brake-on occurs at zero time. The event minimum values given in the figure are simply the minimum values from the entire event analysis time, i.e., from –4 seconds to the end of the event at approximately 5.2 seconds. For example, the range minimum, 27 ft, occurs at the end of the braking event, while the range-rate minimum, -24 ft/s, occurs at approximately 2.5 seconds.

The ΔT and ΔV values of Figure 66 show the duration of the ACC vehicle brake event and the velocity loss during the time while the brake was on. For this particular example, all three of the collision-warning algorithms would have sounded a warning as represented by the number 1 in the columns labeling the three collision-warning algorithms.

Finally, the severity indicators show estimates of acceleration that would have been necessary to avoid a collision during this event. The constant acceleration estimate, -0.2 g, in this case, is the constant acceleration needed by the ACC driver to avoid a crash with the preceding vehicle if this level acceleration were applied at time zero or the ACC brake-on time. (Note: in this case, the preceding vehicle leaves the sensor's view shortly after the brake event ends, so although technically -0.2 g was enough acceleration to prevent a crash, had the preceding vehicle remained a target longer, a larger constant acceleration probably would have been required.) The acceleration to avoid a crash, named Avoid Ax in the figure, shows that the minimum acceleration, by this estimate, was –0.45 g. This measure is calculated by taking the difference between the preceding vehicle acceleration and the acceleration needed to stop given a range and range-rate between the two vehicles. The calculation is done for every time-step during the event and the minimum is reported.

Distributions of FOT manual brake events

The brake event table for the FOT database is given in Appendix H. To summarize these results, a selection of data distributions were created. Figure 67 shows the minimum range and range-rate distributions for the 303 manual events in the FOT database.

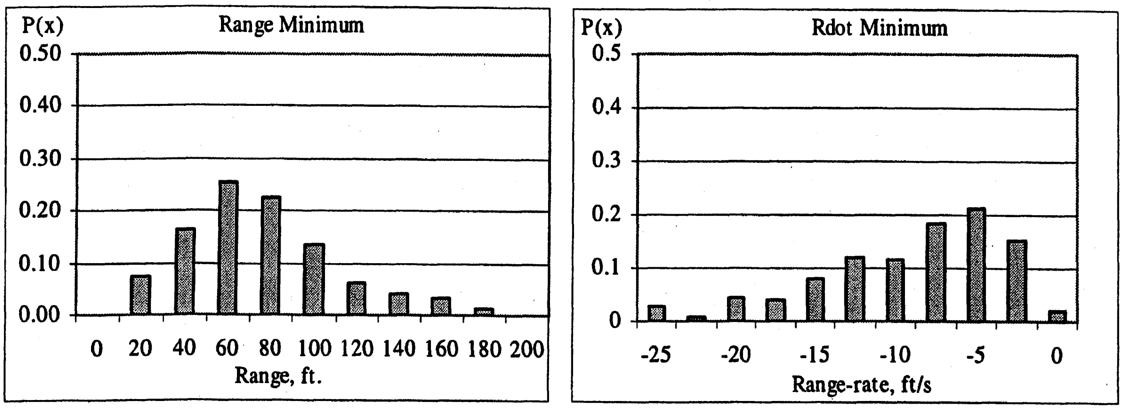


Figure 67. Range and range-rate minimums for the 303 manual FOT brake events

For these events, the most likely minimum range value was between 40 and 60 ft. This accounts for approximately 25 percent of the event set. Minimum ranges between 20 to 40 ft and 0 to 20 ft account for roughly 16 and 7 percent, respectively. In total, approximately half of these conflictual braking events resulted in minimum range values of less than 60 ft. Conversely, only 4 percent of the events resulted in minimum ranges above 140 ft.

The minimum range-rate distribution in Figure 67 shows that in 80 percent of these events the driver of the ACC vehicle did not let the closing rate exceed -15 ft/s while in only 3 percent of the events did the closing rate exceed -25 ft/s. (Note that none of the events involved approaching a stopped vehicle.) To help appreciate the meaning of a range-rate of -15 ft/s, it takes an acceleration level of -0.23 g to reduce this range-rate level to zero in 2 seconds provided the preceding vehicle continues at constant velocity.

Figure 68 shows the distribution of minimum headway-time-margin and time-to-collision for the 303 manual FOT brake events.

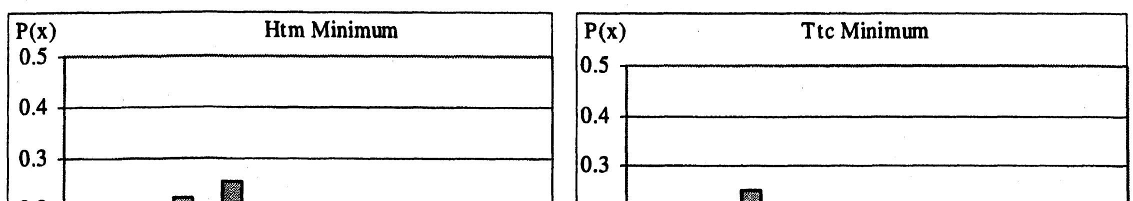


Figure 68. Htm and Ttc minimums for the 303 manual FOT brake events

The minimum Htm distribution suggests that all drivers avoid reaching values of less than 0.25 s. There were only four events where Htm dropped below 0.25s or just over 1 percent of the total number of events. This is markedly different from the adjacent bin, the 0.25 to 0.5 s, where 43 (14 percent) of the events had a minimum in this Htm range.

Table 14 shows the brake event statistics for the four events with minimum Htm between 0 and 0.25 s. These are all high-speed events with initial velocities in the 60 to 70 mph range.

Table 14. Brake event statistics for cases with minimum Htm below 0.25 s

				Preceding Vehicle Brake On						Acc Vehicle Brake On					
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s
Man	87	177	90	15	-1	100	99	0.2	12	13	-2	100	98	0.1	6
Man	41	47	113	15	-2	87	86	0.2	9	16	-2	89	87	0.2	9
Man	56	113	138	27	-7	94	86	0.3	4	27	-7	94	86	0.3	4
Man	4	44	152	26	-3	90	87	0.3	8	27	-3	91	88	0.3	9

Event Minimums						ΔT & V		Warnings			Severity	
Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
-0.13	-0.14	10	-3	0.1	3	1.9	-7	1	1	1	-0.05	-0.07
-0.27	-0.23	14	-2	0.2	8	2.6	-12	0	1	1	-0.05	-0.09
-0.15	-0.14	17	-7	0.2	3	2.8	-10	0	1	1	-0.10	-0.11
-0.40	-0.42	19	-5	0.2	4	2.6	-20	0	1	1	-0.15	-0.21

The brake application time, ΔT, for all four events was similar, ranging from 2 to 3 s. However, only two of the events involved acceleration below -0.2 g and only one of them had an acceleration below -0.4 g. For this speed, a 0.4 g deceleration, at close range, is dramatic. The range value at the start of the event (152) was 26 ft. and the minimum range dropped to 19 ft which implies that both vehicles were decelerating virtually simultaneously. Clearly, the driver of the ACC vehicle was monitoring the preceding vehicle very closely. This is supported by the minimum Ttc and range-rate values which are not extremes relative to the corresponding values in the table and as shown in the range-rate and Ttc distributions. (The minimum Ttc for this event reached 4 s—a level that is not uncommon, noting that there were 52 (17 percent) between 2.5 and 5 s in 303 manual brake events from the FOT. Range-rate reached a minimum of -5 ft/s—a value which falls in the most populated bin of the range-rate distribution above.)

In only one of the four events shown in Table 14 did all three of the warning algorithms sound. From a severity view, the constant Ax and Avoid Ax measures showed accelerations that were less than the actual minimums performed by the driver. Also, neither of the severity measures reached extreme values of acceleration for the forward speeds involved.

The time-to-collision distribution in Figure 68 shows that 14 (5 percent) of the brake events resulted in a Ttc value of less than 2.5 s. The shortest Ttc within this bin was 1.4 s—an event whose record is summarized in Table 15.

Table 15. The brake event with the smallest minimum Ttc

				Preceding Vehicle Brake On						Acc Vehicle Brake On					
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s
Man	56	88	270	94	-1	83	82	1.1	50	95	-1	83	82	1.1	50

Event Minimums						ΔT & V		Warnings			Severity	
Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHTSA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
-0.33	-0.37	8	-12	1.1	1.4	12.3	-83	1	1	0	-0.25	-0.42

This event started with a range of 94 ft and forward velocity of 83 ft/s (56 mph). However, unlike the minimum Htm events described above, the braking in this event lasted for 12.3 s, a relatively long time. The ΔV indicates that the vehicle braked to a stop. The minimum accelerations for the preceding and ACC vehicles were –0.37 and –0.33 g, respectively. These would be considered aggressive accelerations by most drivers, however, the table does not provide an indication of when and at what velocity the minimums occurred, so it is difficult to intuitively judge its severity. An acceleration of –0.3 g while going 55 mph is much more aggressive than a similar level of acceleration while going 10 mph. In fact, a short-coming of the event minimum and avoid Ax values in the brake event table is the lack of a relationship between the table values and the corresponding velocity at the time of their recording.

Further analysis of the 14 Ttc values in the most extreme bin of Figure 68 shows that the event in Table 15 is not anomalous. In fact, the average ΔT for all the events in this bin was 11 s. Furthermore, the average ΔV was -62 ft/s and the average Vdot was -0.33 g. In short, without qualifying these events with either a minimum velocity threshold or a relationship between the event minimums and the corresponding velocity, it is difficult to judge their severity. Certainly, a time-to-collision value of less than 2.5 s is severe at high speeds, but at low speeds it is commonplace.

Figure 69 shows the ΔT and ΔV for the ACC vehicle in the 303 manual FOT brake events. The distributions clearly show that these events were dominated by brake application times of less than 5 s and ΔV of greater than -30 ft/s (20 mph).

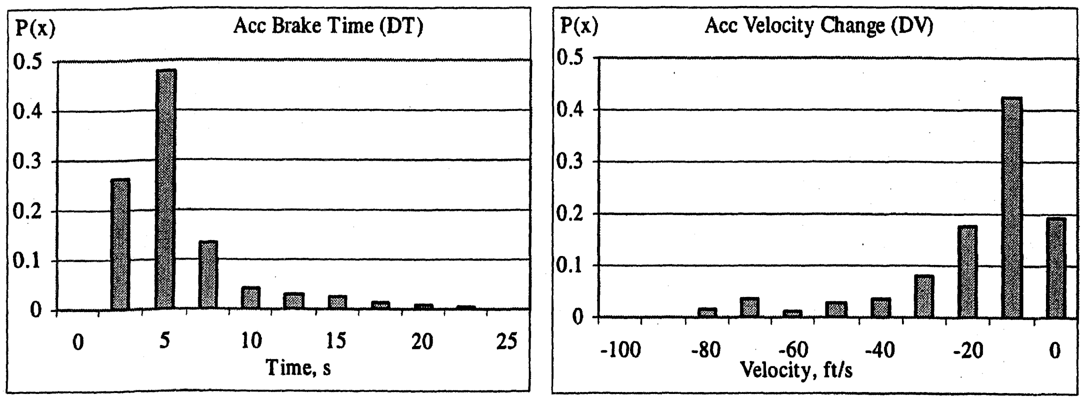


Figure 69. ΔT (brake application time) and related ΔV for the ACC vehicle in the 303 manual FOT brake events

All the brake events (manual, ACC, FOT and FOCAS) are considered high-speed events in that they all were initiated when the ACC vehicle was traveling at 50 mph or greater. This typical duration and velocity change would imply an acceleration of -0.2 g which is close to the average minimum Vdot of -0.25 g for the 303 events. The distributions also imply that most of these brake events did not involve braking to a stop, nor did they include short stab braking events. (The shortest ΔT in the FOT manual events was 1.1 s while the smallest ΔV was 5.5 ft/s.)

Figure 70 shows minimum Vdot, Vpdot and Avoid Ax distributions for the 303 manual FOT brake events. In general, the distributions for Vdot and Vpdot are similar. As the distribution shows, the majority of events involve levels of Vdot acceleration greater then -0.3 g (238 events or 78 percent). However, there were 65 events involving Vdot accelerations below -0.3 g. Considering that these data were selected from 68,000 miles of manual driving, one would infer that high-speed braking events of this nature occur on average about every 1000 miles per driver. This may be infrequent for the individual driver (10 or 12 occurrences per year), but important in the sense of exposure of the driving population as a whole.

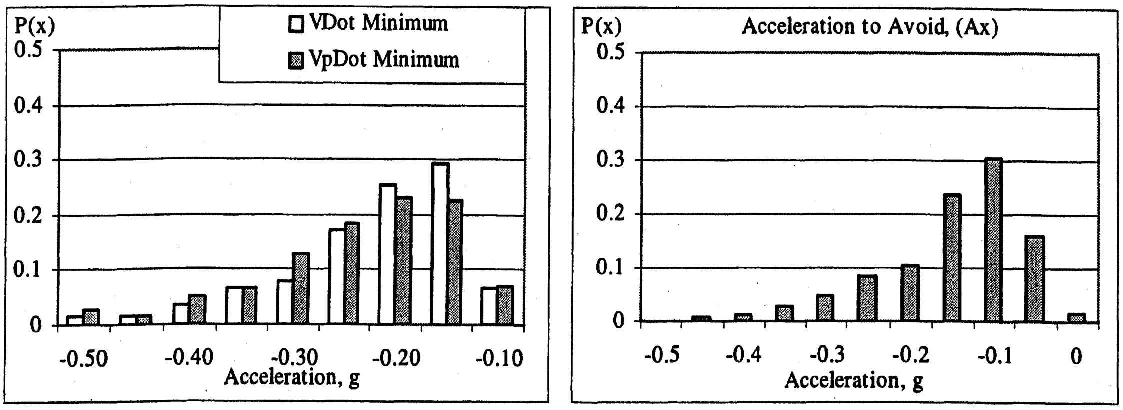


Figure 70. Minimum Vdot, Vpdot and acceleration to avoid a crash for the 303 manual FOT brake events

The Acceleration-to-Avoid distribution in Figure 70 has a similar shape to the minimum Vdot and Vpdot distribution. One notable difference, however, is that the level of acceleration for the Avoid distribution is shifted by approximately 0.05 g. The minimum Vdot and Vpdot distribution peaks at -0.15 g whereas the Avoid distribution peaks at -0.1 g. Conceptually this makes sense. The Avoid numeric assumes an acceleration that would bring the vehicle to a stop at the bumper of the preceding vehicle. Thus it would underestimate what actually happens if not for the simple reason that drivers will choose to have some range remaining between them and the preceding vehicle during a braking maneuver.

5.4.3.2 Collision-warning results

Three collision-warning algorithms are computed using brake events measured in both the FOT and FOCAS databases. The three algorithms are called NHTSA, Ttc, and Vcdot to distinguish them. Each algorithm is defined algebraically in section 5.4. This section presents the results of exercising these three algorithms using the manual braking events from the FOT data set. The purpose of this analysis is to develop an understanding of when and how frequently warnings would be given. The Ttc (time to collision) algorithm is based on circumstances corresponding to situations that appear stressful to drivers. To the extent that drivers will feel that they should be warned in these situations the Ttc algorithm represents a basis for comparison. In this context, the following results indicate that the NHTSA and Vcdot algorithms do not warn in many situations that are stressful to drivers.

Parameter settings for the three algorithms

Each of the three algorithms have a set of limits or thresholds that define the sensitivity of the warning. The NHTSA algorithm used a 1.5 s lead time, a -0.75 g acceleration, and a final minimum range of 7 ft. in the warning analysis. The VcDot rule had an acceleration threshold of -0.4 g for the calculated VcDot and a -0.2 g threshold for Vdot. The Ttc algorithm used a value of 10 s as its threshold to warn. All three algorithms had a 0.3 s time lag for activation. In other words, the conditions for warning had to be true for three consecutive time steps (10 Hz data samples) for a warning to be issued. As mentioned before, the analysis was done on the same events outlined above for brake events including the use of a 4.0 s preview before each brake event.

The warning analysis table

To summarize the results of the three warning algorithms, a table was compiled that lists the conditions at the time the warning was issued. For example, Table 16 on the next page shows the warning analysis table for the FOCAS brake events that were presented earlier in Table 12.

There are four categories in the table. The first shows the event classification with identification parameters that show the control mode and pointers necessary to align this event with the brake event and the wait-time tables. Note: A blank set of fields for a warning type in the table indicates that the warning was not triggered for the corresponding algorithm. For the FOCAS brake events, there were no warnings issued by the NHTSA algorithm so these fields have been left out of Table 16. Similar tables for the ICC FOT data are included in Appendix I. The definitions of the columns in the warning analysis tables are shown in Table 17.

Table 16 Example collision warning analysis table for FOCAS warning events.

					Ttc Warning								VcDot Warning							
Cntrl	Drv	Trip	#	Avoid Ax, g	R, ft	Rdot, ft/s	V, ft/s	Vdot, g	VpDot, g	Htm, s	Ttc, s	Wn-Bk Time,s	R, ft	Rdot, ft/s	V, ft/s	Vdot, g	VpDot, g	Htm, s	Ttc, s	Wn-Bk Time,s
Man	13	563	1	-0.16	42	-5	77	-0.02	-0.07	0.5	8.1	0.61	36	-7	74	-0.06	-0.12	0.5	5.2	1.21
Man	9	555	2	-0.20	101	-12	91	0.00	-0.17	1.1	8.6	0.11								
Man	13	563	4	-0.10	37	-4	89	0.00	0.00	0.4	9.0	**-3.19**	30	-4	87	-0.03	-0.02	0.4	7.1	**-1.81**
Man	14	564	6	-0.18	62	-7	75	-0.11	-0.17	0.8	9.2	1.71								
Man	12	561	8	-0.14	50	-6	86	-0.03	-0.08	0.6	8.4	0.60								
Man	21	585	10	-0.17	34	-4	88	-0.13	-0.14	0.4	8.8	1.53								
Man	19	581	11	-0.27	61	-7	94	-0.06	-0.13	0.6	8.7	1.20	53	-9	91	-0.09	-0.17	0.6	5.7	1.81
Man	3	533	13	-0.12	89	-9	##	-0.05	-0.09	0.9	9.4	0.99								
Man	11	559	15	-0.20	120	-15	##	0.02	-0.16	1.2	8.2	**-0.49**	106	-18	101	-0.01	-0.16	1.0	6.0	0.22
Man	3	533	16	-0.10	52	-6	97	-0.05	-0.09	0.5	9.0	0.99								
Acc	21	585	1	-0.16	111	-12	##	-0.07	-0.11	1.1	9.2	0.88								
Acc	24	592	2	-0.14	101	-11	92	-0.04	-0.12	1.1	9.5	1.21								
Acc	8	554	4	-0.16	129	-13	98	-0.10	-0.14	1.3	9.9	1.71								
Acc	7	550	5	-0.22	72	-9	83	0.02	-0.08	0.9	8.1	**-0.28**	60	-13	79	-0.06	-0.16	0.8	4.7	0.49
Acc	19	581	8	-0.19	101	-11	##	-0.02	-0.11	1.0	8.9	0.83	82	-14	93	-0.12	-0.15	0.9	6.1	2.14
Acc	12	561	9	-0.16	45	-6	##	0.00	-0.13	0.4	8.0	0.50	44	-6	101	0.00	-0.13	0.4	6.9	0.66

Table 17. Definition of fields in the collision-warning table

Category	Field	Description
Event Classification		Identification parameters
	Cntrl	Control mode: Man = manual control; ACC = adaptive cruise control
	Drv	Driver identification number
	Trip	Trip identification number
	#	Sort number (sorted in same order as table E-1 in Appendix E)
	Avoid Ax	The minimum acceleration needed to avoid a crash as measured during the time of the event: Avoid Ax=Vpdot-((Rdot)*(Rdot)/(2*R))
Warning Type		Algorithm used, either NHTSA, Ttc, or VcDot
	R	Range, ft, to the preceding vehicle at the time of warning
	Rdot	Range-rate, ft/s, to the preceding vehicle at the time of warning
	V	Velocity, ft/s, of the ACC vehicle at the time of warning
	Vdot	Acceleration, g, of the ACC vehicle at the time of warning
	Vpdot	Acceleration, g, of the preceding vehicle at the time of warning
	Htm	Headway-time-margin, s, to the preceding vehicle at the time of warning
	Ttc	Time-to-collision, s, to the preceding vehicle at the "Brake On" time
	Warn Time	The time difference, s, between when the warning sounded and when the driver applied the brake. (A negative number indicates the warning sounded before the driver applied the brake.)

FOT manual warning events results

The number of warnings issued by the three different algorithms differed considerably for the tested set of parametric inputs. The least number of warnings, 20, was given by the NHTSA algorithm from the set of 303 braking events. This was followed by the VcDot algorithm which issued 78 warnings. The Ttc algorithm issued the most warnings at 201. The figures below summarize the results from the manual FOT warning events table. This table can be found in Appendix I. In these figures the values for each warning algorithm were sorted in ascending order and then plotted as a cumulative distribution.[2]

Figure 71 shows the distributions (Cd(x)) of velocity and ACC vehicle acceleration for the three different algorithms. The x-axis shows the value at the time of warning, while the y-axis is the normalized count. Clearly the velocity trace looks markedly different for the NHTSA algorithm. For this set of braking events, it is clear that some consideration to velocity would be necessary if the NHTSA algorithm were to be implemented as tested in this project. All the events began at velocities above 73 ft/s (50 mph). The figure shows that in 95 percent of the cases the Ttc and Vcdot warning were

[2] The results are displayed this way due to the wide variation in the number of warnings issued by the three warning algorithms.

issued at velocities above 66 ft/s (45 mph). In contrast, the NHTSA algorithm issued over 70 percent of its warnings at speeds below 66 ft/s.

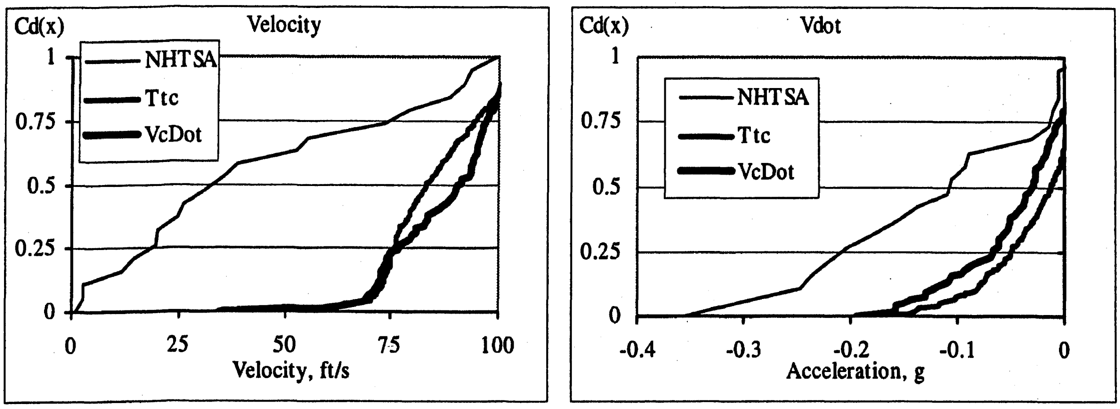


Figure 71. Distributions of velocity and acceleration for the three different algorithms

Furthermore, from an acceleration standpoint, the NHTSA algorithm results were different from the results for the other two algorithms. The figure shows the NHTSA warning was issued at much higher levels of acceleration relative to the other two algorithms. Given that acceleration is an indication of driver braking level, it is clear that the NHTSA algorithm (and to a lesser degree Ttc and Vcdot) issued warnings while the driver was in the process of braking.

Figure 72 shows range and range-rate values at the time of warning for the three algorithms. The range distributions are markedly different for the three algorithms.

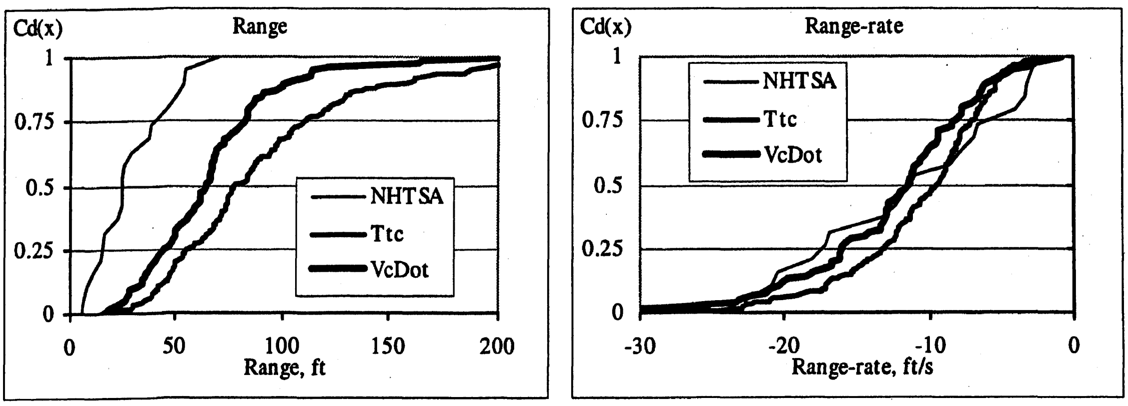


Figure 72. Distributions of range and range-rate for the three different algorithms

Clearly, the NHTSA warning was sounded at much closer ranges than the other two algorithms. In fact, 25 percent of the NHTSA warnings were at 15 ft. However, velocity needs to be considered when assessing the threat of close-range driving and hence the headway-time-margin measure (Range/Velocity) as shown in Figure 73 becomes more meaningful. Figure 73 is discussed in more detail below. For the other two warning algorithms, the measured range varied from approximately 25 to 175 ft. with the Ttc warning typically issued at longer ranges compared to the Vcdot rule. The range-rate results, shown in Figure 72, for the three algorithms are similar. In general, about half the warnings for each algorithm were given with range-rate values less than –11 ft/s.

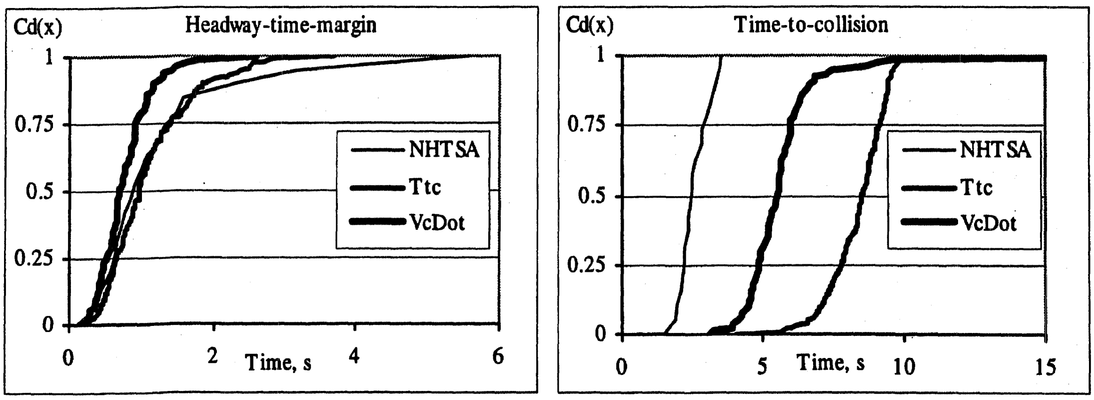


Figure 73. Distributions of headway-time-margin and time-to-collision for the three different algorithms

Figure 73 shows the headway-time-margin and time-to-collision warning results. These measures have markedly different results for the three rules. In the Htm plot, the algorithms all behaved similarly at Htm values below 1 s. At larger Htm values, the NHTSA and Ttc rules are in agreement, while the VcDot rule is less conservative in a safety sense since it warns at smaller Htm values relative to the other two rules.

The time-to-collision plot in Figure 73 is the most striking illustration of differences in the three rules. The figure clearly shows that the NHTSA algorithm will issue warnings at much smaller Ttc values than the VcDot or the Ttc rule itself. Using just the 50 percentile value, the NHTSA algorithm would sound at 2.5 s while the VcDot and Ttc warnings would sound at 5.5 and 8.5 s, respectively.

Warnings and braking

Based on the results in this section, it seems likely that any successful warning algorithm will have to consider actions by the driver along with the kinematics and inter-vehicular relationships of the current situation when deciding whether to warn or not. Certainly, there are situations when the driver's attention is completely dedicated to the task of longitudinal control, both position and speed, and in those situations, sounding a warning may be more disturbing than helpful. However, assessing the driver's level of alertness or attention is a challenge. One simple technique to better understand what the driver is doing is to consider whether the brake is being applied. The assumption here is that, when braking, it is very likely that the driver's attention is focused on the driving task per se. Therefore, a "smarter" algorithm would consider braking in its criteria for warning. Using the results generated with the manual FOT braking events, a simple numeric was calculated that showed the difference in time between when the driver of the ACC vehicle began braking and when the warning was issued by the three different algorithms. This measure is simply defined as the warning time minus the brake application time. To interpret the measure, a negative value means the warning sounded before the brake was applied and a positive value means the brake was applied during the warning.

Figure 74 and Table 18 show the results of this analysis. The figure is plotted such that a negative time along the x-axis represents the cases where the warning was issued before the brake application, while a positive time value means the warning was issued during braking. In this simple analysis, the difference between the three algorithms is clear. The NHTSA algorithm had only one case where the driver was not already braking when the alarm sounded. For this one case, the figure shows, the warning and brake application occurred almost simultaneously. The Ttc and VcDot algorithms had close to 25 percent of their warnings before braking. These numbers are also illustrated in Table 18.

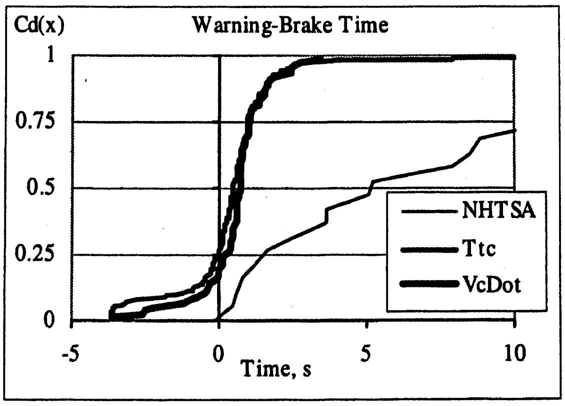


Figure 74. Warning time minus brake time for the warning results

Table 18. Warning counts and brake pedal application for the ICC FOT manual data

	All	Prebrake	Postbrake
NHTSA	20	1	19
Ttc	201	55	146
VcDot	78	16	62

These results were simply based on using the brake pedal switch as an indicator of what the driver is doing and thinking. However, other more complicated rules could be used. For example, one FCW algorithm may consider the position of the throttle (assuming that the driver will need more time to switch to and apply the brakes) and the brake when deciding to warn. Or perhaps the level of deceleration is important if the driver is pressing the brake pedal. Whatever the rule, it will be important for the driver to understand when and how it is best used to help manage the longitudinal driving task.

5.4.4 Findings and Recommendations

Evaluation of three FCW systems showed that

1. regardless of the systems tested, the quality of the measured signals of range, range-rate and velocity in the ICC FOT require use of a data-smoothing routine. This study found that Kalman filter theory resolved many of the data quality issues and hence reduced the number of false alarms in the simulated FCW routines.

2. the FCW algorithms were tested using a subset of the ICC FOT and FOCAS databases. This subset was a set of braking events that involved significant decelerations in both the preceding and following vehicles. Analysis of these events resulted in tables that characterize the brake events by:

   - listing all the pertinent variables (Range, Range-rate, and Velocity and derived variables of Vp, Htm, and Ttc) at the time of the preceding vehicle "brake on" and at the time of the ACC vehicle brake application

   - reporting the minimum values of Vdot, Vpdot, Range, Range-rate, Htm and Ttc during the brake event

   - listing the time of the brake application and the change in velocity of the ACC vehicle, and

   - measuring the severity of the event by calculating two decelerations values.

3. of the 303 manual ICC FOT braking events only 65 involved Vdot decelerations below –0.3 g. Considering that these data were selected from approximately 68,000 miles of manual driving would imply that high-speed braking events of this nature occur about every 1000 miles per driver.

4. the number of warnings issued by the three different algorithms differed considerably for the tested set of parametric inputs. The least number of warnings, 20, was given by the NHTSA algorithm from the set of 303 braking events. This was followed by the VcDot algorithm which issued 78 warnings. The Ttc algorithm issued the most warnings at 201.
5. in 95 percent of the cases the Ttc and Vcdot warning were issued at velocities above 66 ft/s (45 mph). The NHTSA algorithm issued over 70 percent of its warnings at speeds below 66 ft/s.
6. the NHTSA algorithm warning was issued at much higher levels of acceleration relative to the other two algorithms.
7. the range distribution is different for the three algorithms. The NHTSA warning was sounded at much closer ranges than the other two algorithms. In fact, 25 percent of the NHTSA warnings were at a range of 15 ft.
8. the NHTSA algorithm will issue warnings at much smaller Ttc values than the VcDot or the Ttc rule itself. Based on the 50^{th} percentile value, the NHTSA algorithm would sound at 2.5 s while the VcDot and Ttc warnings would sound at 5.5 and 8.5 s, respectively.
9. the NHTSA algorithm had only one case where the driver was not already braking when the alarm sounded, while the Ttc and VcDot results showed that close to 25 percent of their warnings were issued prior to braking.

5.5 Vigilance vs. Deceleration Authority

5.5.1 Research Activities

A computational method, based upon test data from the ICC FOT, was employed for estimating the respective frequencies of braking intervention by drivers operating with adaptive cruise control systems that have differing levels of deceleration authority. Estimations to represent response with other ACC controllers employed the actual test data up to a notable point in the pre-intervention sequence, followed by a computation that assumed alternative deceleration rules. This issue was examined because of its assumed implications for the vigilance of the ACC driver, recognizing that the vigilance literature (as reviewed briefly, below) shows humans to be less ready to execute an occasional task, from a state of continuous monitoring, if the task arises infrequently.

When the braking authority of an ACC controller is relatively high, the driver finds that a great portion of all headway conflicts can be automatically managed by the system, such that the time or travel distance between necessary interventions can be very long, indeed.

The distinction of necessary vs. discretionary interventions seems useful, in this discussion, because it is very clear from the ICC FOT data that more than half of all driver interventions using the brake pedal occur under conditions that the controller could very well have managed. Thus, the driver often exercises an intervention for reasons other than the occurrence of an excessive conflict in headway space. Since discretionary interventions appear to express a strongly anticipatory kind of reasoning on the part of the driver—associated, for example, with intent to change lanes, preparing to exit a freeway, and simply choosing to terminate engagement in light of the traffic context—their occurrence is not thought to require vigilance in the sense of continued close monitoring of the immediate headway condition. Thus, if the cognitive disposition of the driver that is needed for necessary intervention implies a certain vigilance that is quite unlike that which stimulates discretionary interventions, then it appears useful to categorize and count the necessary interventions as a means of grading differing ACC controllers for their possible impact on the retention of necessary-intervention vigilance.

In the analysis conducted here, the phenomenon of manual intervention on ACC was first examined within the FOT data in order to determine a useful definition for the point of necessary intervention. Then computations were performed to pose a "what if" scenario that employs each of a few differing ACC controllers under the same necessary intervention cases seen in the field test. The results serve to express the comparative travel periods over which differing ACC systems could stay in engagement, based upon their respective levels of decel authority for resolving the headway conflicts that develop.

On the matter of vigilance, per se

The above-mentioned portion of the study examined the issue of vigilance under ACC control, drawing from the literature on vigilance, as well as empirical measurements from the FOT that enabled us to scale the time periods over which vigilance must be sustained, between interventions. In a nutshell, the operating hypothesis is that while an elevated level of deceleration authority might enhance comfort, utilization, and even safety by virtue of the routine conflict management performance of the ACC controller, the sheer infrequency of intervention events with high-decel systems raises a concern for lapsed vigilance.

Vigilance implies wakefulness or the keeping of a watch. The classical assignment of sentries and, in modern times, operators of radar screens, power plants, etc., invokes the image of a continuous assignment during which one's readiness to detect a threat and respond is central to the task. A very great volume of literature exists on this general subject, although very little of it seems to pertain unambiguously to the scenario of a driver supervising ACC control. Nevertheless, underload in the watchkeeper's task and the mere passage of time are the foundational characteristics which gives rise to the so-called vigilance decrement first reported by Mackworth [23]. The sparsity of a stimulus is seen as the central element posing an incapacity in human performance— for example, as captured in the well known arousal model of Frankmann [22], accounting for a decline in detection performance over time. Moreover, it is difficult to remain vigilant if the thing for which you are watching rarely appears.

Much of the vigilance literature addresses the question of detection performance, or the recognition that a watched-for event has indeed occurred. Dember [21], for example, concern themselves with detection over long periods of watch-keeping, noting that the perceived workload of vigilance appears to grow with time-on-task. The broad question of detection or monitoring performance, especially under conditions of partial automation, poses a task for which humans seem to be poorly suited (e.g., Molloy [24], Davies [20], Wiener [25]). Human failure under such circumstances is normally associated with failure to take a corrective action that is otherwise obvious or intuitive. Wiener [25], for example, examined two specific incidents in commercial aviation in which the crews of 747 aircraft suffered major loss-of-control events when, after a period of several hours of flight, automation failure occurred without their noticing highly discriminable indicators of the problems. Moreover, the vigilance decrement as a detection handicap has been one of the most consistent findings in studies of sustained attention by Ceplenski [19].

The other characteristic result of lapsed vigilance is simple latency in responding to a detected threat. Johnson [28] showed a 20% growth in reaction times over the 3-hour duration of duty in a simulated army sentry task, for example, but the relative frequency of his target stimuli suggest that growth in latencies may have derived more from fatigue than from sparsity of stimulus. Increased reaction times resulting from sparse stimuli have been reported by Molloy [24], for differing levels of complexity in a baseline task. Molloy and others have addressed such performance decrements in connection with monitoring cockpit automation functions for infrequent but critical system faults, citing the central concern for over-reliance on a highly reliable but not quite comprehensive control aid.

5.5.2 Analysis Methodology

Data collected during the ICC FOT were analyzed for both (a) observation of the braking intervention behavior of test subjects driving with a low-authority ACC system and (b) computation of the braking intervention rate that would attend controllers having alternative levels of deceleration authority.

From the total of 31,838 miles of ACC-engaged driving that were logged in the FOT at speeds above 55 mph, a set of 756 braking intervention events were culled based on the following selection constraints:

- ACC intervention was achieved by depressing the brake pedal;
- the velocity at brake application was greater than 55 mph;
- the velocity at brake release was greater than 0 mph;
- the ACC control system was acting on a preceding vehicle in the sense that the commanded velocity was less than the driver-selected set speed;
- the brake interventions lasted longer and resulted in more deceleration than found in a brake tap scenario whose deceleration level was less than 0.05 g or whose duration was less than 1 second;
- the preceding vehicle had an average deceleration of at least -0.02 g during the time of the host driver's brake pedal application; and
- the same preceding vehicle was present throughout the brake event.

The cumulative distribution of headway-time-margins, Htm, at which intervention occurred in these cases is shown in Figure 75, expressed in seconds. Shown in Figure 76 are the same data, except normalized by the prevailing value of driver-selected headway time, Th. The data in these two figures portray rather clearly that the driver's choice of when to intervene is highly conditioned by the initial Th selection, presumably because the selected value reflects both the headway preferences and conflict tolerances of the individuals involved.

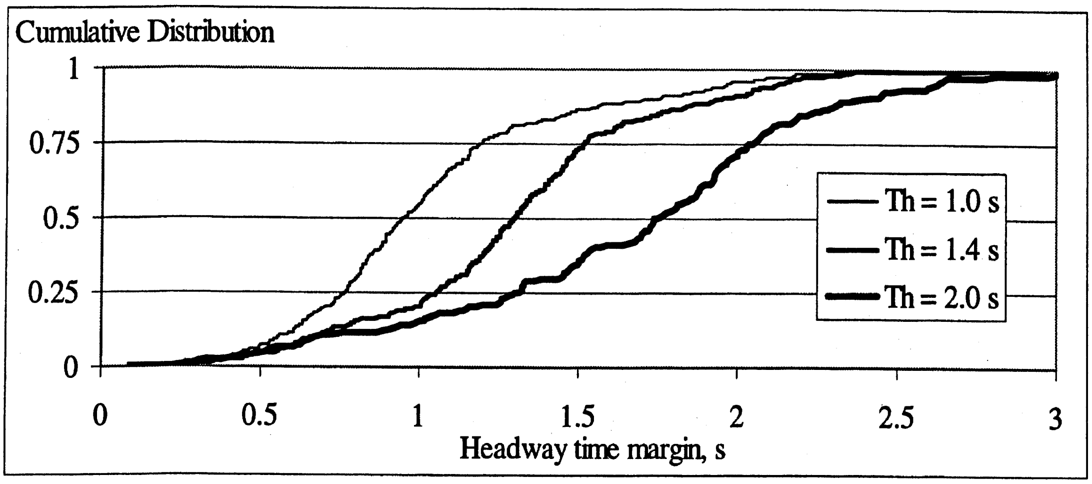


Figure 75. Headway-time-margin at the time of brake intervention

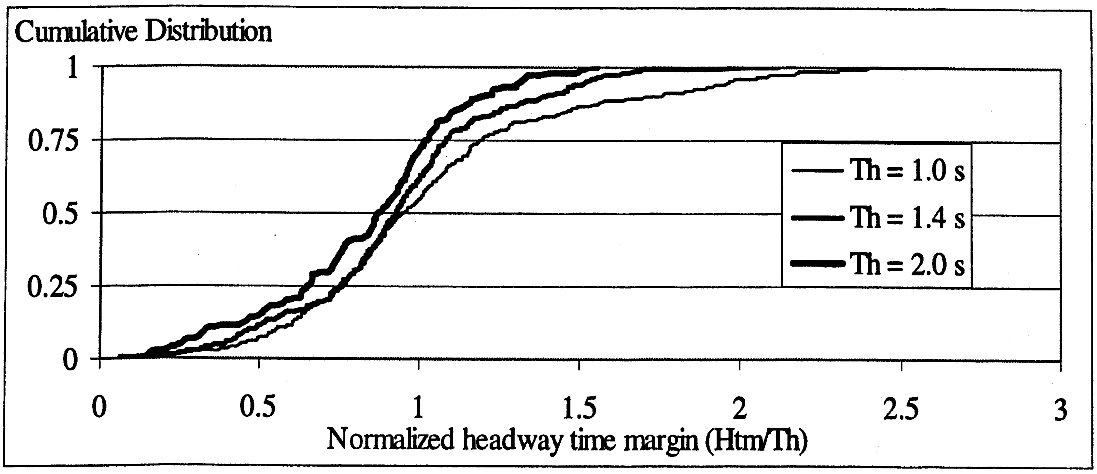


Figure 76. Normalized headway-time-margin at the time of brake intervention

One attractive possibility for combining the R, Rdot, and Vpdot condition variables, is to project the minimum headway time, Htm_{min} *that would have prevailed* if intervention had not occurred and if the ACC controller had stayed active. That is, the Htm_{min} projection looks forward in time beyond the point at which intervention did occur, to the point at which the ACC controller would have either rendered Rdot = 0 or crashed.

One measure of this kind was reported in a paper by BMW researchers studying ACC braking interventions (Kopf [26]), whereby the Htm_{min} value was computed for the moment of intervention to show the nominal severity of the conflict to which the intervener was responding. The concept of a predicted Htm_{min} is attractive as a descriptor of the intervention moment because it portrays a form of mental model that the driver may well be using to anticipate whether intervention is necessary. The notion is that an experienced ACC user should have learned, by exposure to the control response of the system during many episodes of headway conflict, how to appraise each developing conflict in terms of the extent of overshoot that will develop if the controller is permitted to manage the situation, without intervention. Thus, a prediction of Htm_{min} serves as a conflict characterization, expressing a variable that should reasonably relate to the driver's intervention behavior. Kopf [26] showed that much of their data is summarized by the conclusion that driver intervention occurs whenever Htm_{min} would have reached less than 0.7 times the desired headway time, Th, given the deceleration authority of the installed ACC controller. That is, the BMW research also showed that the choice to intervene does follow the Th setting which the driver has selected. Thus, Htm_{min} can be usefully normalized by dividing it by the desired headway time value.

The data shown earlier in Figure 76—although representing the instantaneous value of (Htm/Th) rather than the forecasted minimum value (Htm_{min} /Th)—do indicate that as many as about 25% of the interventions by FOT drivers occurred when (Htm_{min}/Th) would have been forecasted to fall below 0.7, suggesting that the FOT drivers were operating somewhat less conservatively than the drivers in BMW's experiment, at least in a substantial portion of the cases. (Note that the prediction value, (Htm_{min} /Th), will always fall at or below the actual intervention value of Htm/Th that are shown in Figure 76 if Rdot is still negative at the time of manual brake onset.)

In any case, it is clear that while a fairly broad range of (Htm/Th) values did prevail at the moment of manual brake interventions in the FOT, the "necessary" set of these events certainly lie at the more severe end of the spectrum, where (Htm_{min} /Th) is approaching zero. Noting the BMW results in which intervention occurred when (Htm_{min}/Th) < 0.7, and yet the apparently greater tolerance of UMTRI's FOT subjects for conflict, without intervention, the value, (Htm_{min} /Th) $= 0.5$ was selected as the threshold of conflict severity beyond which an intervention would be defined as *necessary*. The necessary intervention would thereby reflect a driver's mental rule that could be stated as follows: I will intervene with the brake whenever I anticipate that the ACC controller would be unable to prevent an intrusion into headway values shorter than half of my selected Th time.

Comparison of alternative controllers according to this threshold would then serve as an instructive means of evaluating differences in necessary-intervention frequency, in service.

Before taking FOT data gathered with one ACC controller and using its intervention-causing conflicts to study other controllers, however, we should first acknowledge that ACC *utilization* will also be significantly affected by the deceleration authority of the

ACC controller. People driving with a higher-authority controller are expected to remain comfortable with ACC engagement under a set of rather dense and conflicted traffic streams for which the FOT drivers, with their low-authority controller, would have chosen manual driving. Thus, it is not possible to use FOT data to study intervention behavior *under traffic conditions that were not included* among the ACC-engaged miles in the FOT. Nevertheless, it is reasonable to employ the FOT intervention cases as a set for studying the impact of other hypothetical ACC controllers *under the same conditions* as those in which FOT drivers utilized ACC control. Clearly, this driving segment lies on the more moderate end of the entire traffic density spectrum. It does, however, happen to include the regime of less congested, rural freeway driving in which the issue of retained vigilance should be most applicable.

Employing FOT data for studying intervention occurrence with other ACC controllers thus focuses on a very particular hypothetical question that can be phrased more or less as follows:

> what if the same FOT drivers had driven in the same traffic, with the same driving manner—in terms of Th selections, lane choices, passing patterns, etc.—but with another ACC controller? Assuming this match in driving conditions, but allowing for higher-authority responses to those headway transients that provoked the necessary braking interventions in the FOT, what would the same set of conflict conditions have provoked in the way of necessary braking interventions with higher-authority ACC systems?

To conduct such "what if" calculations using the 756 cases that fell in the defined set of manual brake interventions in the FOT, we need to simply model each of the alternative ACC controllers so that its management of the developing headway transient reflects its control authority. A simple means of representing this control process is to use the simple quasi-static modeling approach that was reported by the Collision Avoidance Metrics Program, CAMP [27], (albeit that CAMP used this approach to study brake applications in the collision-warning context). The approach is to employ ACC vehicle deceleration, beginning at a start time, T_s, according to a continuously computed deceleration applied value, D_{app}, beginning with the initial R_s and $Rdot_s$ values prevailing at time T_s and targeting as the objective in each time step the arrival at a minimum range value, $R = 0.5ThV$. (That is, the ACC controller would be set to apply increasing deceleration, up to its maximum authority, per a rule that sought to avoid overshooting the value, $(Htm_{min}/Th) = 0.5$.)

The D_{app} expression at each i'th time step would be of the form,

$$Dapp\ i = [(Vpdoti) - ((Rdoti)^2 / 2(Ri - 0.5ThVi))] \qquad (5.24)$$

Where:

Rdot is initialized at $Rdot_s$ and continuously computed, thereafter,

R is initialized at R_s and continuously computed, thereafter,

Vpdot is drawn at each time step directly from the FOT data, and

Dapp is limited to < Dauthority and, sustains the value, Dauthority, whenever R has fallen below the targeted minimum, 0.5ThV.

The computation begins at time, T_s which is determined by looking back from the time of intervention to the point at which either Rdot transitions from a positive to a negative value or the ACC vehicle first acquires the preceding vehicle as its primary target. The computation continues to run using equation (5.24) until either (a) R <= 0, (b) Rdot > 0 for two seconds, (c) V = 0 or (d) the preceding vehicle is lost as a target.

5.5.3 Results

Shown in Figure 77 is a cumulative histogram of results from the computation of (Htm_{min} /Th) for four different ACC controllers in the 756 cases that had precipitated a manual braking intervention on ACC control during the FOT.

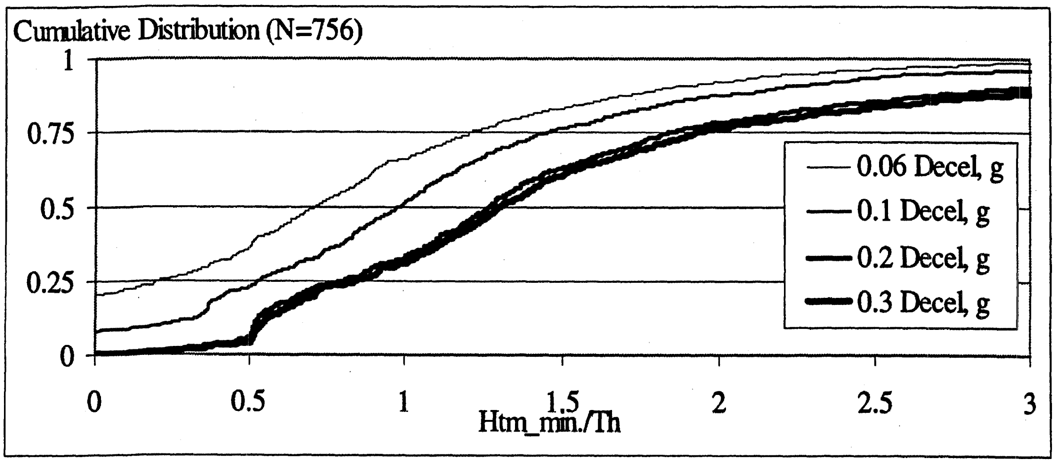


Figure 77. Cumulative distribution of Htm_{min}/Th for different ACC controllers

The histogram shows, firstly, that the 0.06 controller used in the FOT system would have crashed (i.e., (Htm_{min}/Th) = 0) in approximately 20 percent of the cases for which drivers intervened in the actual test. In approximately 30 percent of the cases, it appears that the driver intervened when the (Htm_{min} /Th) response would have fallen below the value of our reference description for a necessary intervention, that is 0.5. Conversely, some 70 percent of the manual brake interventions observed in this set of FOT events were of the "discretionary" type, lying above the 0.5 value of Htm_{min} /Th, although drivers saw fit to intervene, nevertheless.

Looking now at results covering the three alternative ACC controllers in Figure 78, we see that the higher-deceleration systems clearly serve to reduce the number of conditions in which a necessary intervention would have prevailed. The contrasting frequencies of necessary interventions and crash events are shown in Figure 78, and Figure 79. Figure 78, presents the count, out of the 756 candidate cases, of the number of events which fall into the necessary intervention window or which would have yielded a crash with each respective controller, if intervention does not occur. Figure 79 shows the net driving distance that one could travel between events that pose a necessary-intervention level of conflict.

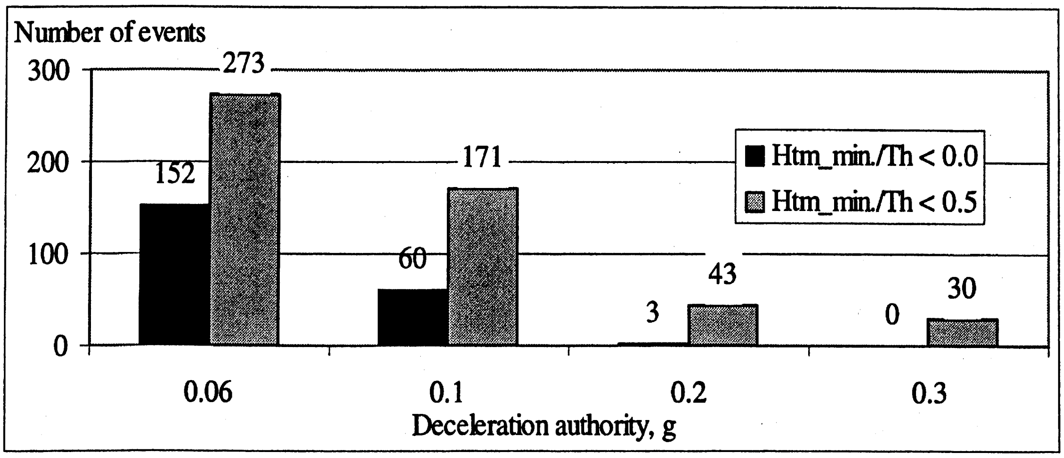


Figure 78. Counts where Htm_{min}/Th < 0 and 0.5 for different ACC controllers

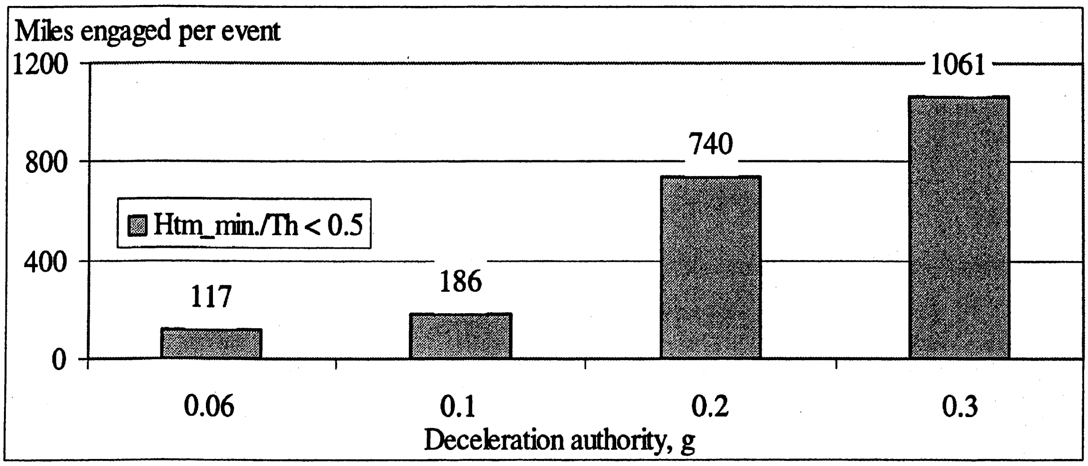


Figure 79. Engaged miles per event for Htm_{min}/Th < 0.5 for different ACC controllers

5.5.4 Findings and Recommendations

Study of Intervention Vigilance vs. ACC Deceleration Authority

The summary data from computations of necessary intervention events, for each of several example levels of ACC deceleration authority show the following:

1. the frequency of occurrence of necessary interventions varies by a factor of 9:1 across the range of controllers considered, and the incidence of events yielding a crash, failing driver intervention, vanishes rapidly as the deceleration authority rises.
2. the frequency of necessary interventions reduces by a factor of 4, and the incidence of crashing decreases by a factor of 20 when the deceleration authority is increased from 0.1 g to 0.2 g. Thus, the largest increment in the apparent utility of ACC to the driver has been accomplished when the deceleration authority reaches 0.2 g.
3. the entire set of results for the 31,838 miles of FOT driving with ACC engaged above 55 mph could have been driven using a 0.3 g ACC controller without having had a single crash into the preceding vehicle, even if no driver had ever intervened by depressing the brake.
4. the apparent saturating character of the frequency of necessary interventions for the 0.3 g controller relative to the 0.2 g system appears to be due to a residual number of close-headway, cut-in episodes that involve less than Htm/Th = 0.5 at the moment of cut-in. Thus, even as the controller authority level rises, the necessary intervention criterion is met as soon as the cut-in vehicle appears within the lane. Clearly, this phenomenon would seem to ensure that at least some residual frequency of braking intervention will occur in response to cut-ins, thus serving to refresh the driver's sense of vigilance as an intervener, regardless of the actual magnitude of ACC deceleration authority.
5. the indicated values of miles of travel between necessary-intervention events show that drivers would travel on the order of 1,000 miles, in ACC engagement, between necessary intervention events if using controllers that lie in the 0.2 or 0.3 g range of deceleration authority levels considered here.

Implications of these Findings for Vigilance in ACC operation

While the vigilance literature is qualitatively instructive, it does not offer guidance for estimating the influence of the computed intervention periods on the vigilance of ACC drivers. Nevertheless, it is rather clear that ACC-with-braking will provide an exceptional reduction in driver workload associated with headway-keeping task. In basic terms, of course, we see that ACC-with-braking has assumed almost all of the headway-keeping assignment, at least as it regards the management of conflicts between the host and the immediately preceding vehicle. When it comes to necessary interventions that occur only once every thousand miles or so, it is easy to show that a one-second lapse in attention under ACC control would have on the order of a 1 in 50,000 chance of coinciding with a necessary intervention event. Thus, it seems almost certain that drivers would perceive this situation as offering an underload relative to the conventional driving task, perhaps encouraging them to devote at least some attentional resources elsewhere.

On the other hand, ACC responds to all forward conflicts by initiating a deceleration response, such that the driver's attention may be drawn back to the forward scene rather quickly by the deceleration cue. Thus, the key handicap that a work underload situation might provoke may not be associated with inattention to the intervention prospect, itself. Rather, driver performance may suffer in two other areas, namely:

1. Drivers may be delayed in appraising and reacting to a rarely appearing conflict that does, indeed, necessitate intervention, even though the ACC deceleration cue has drawn their attention to the conflict. A qualitative expectation of this kind is supported by the vigilance literature. Most ACC systems are also expected to sound an audible alert when the current conflict invokes the full deceleration authority of the system. But the time taken while deciding to intervene, as well as the reaction delay in any intervention that is decided, may only begin after the deceleration cue and audible alert have been manifested. In any case, the mere infrequency of the necessary-intervention stimuli suggests poorer intervention performance due to vigilance decrements that are well documented in the literature.
2. ACC drivers may also tend to divert attention from the driving process as a whole. This expectation has been confirmed in anecdotes conveyed by several of the FOT subjects. By a sort of reductive error, the driver may unconsciously assume that if no ACC deceleration cue is apparent, no driving conflict *of any kind* prevails. That is, since headway conflicts tend to impose so much of the normal driving burden, their almost total resolution by ACC may cause drivers to unintentionally reduce the domain of their conflict vigilance to the headway modality, alone, given that it is so handily cued by ACC deceleration responses, plus the occasional audible alert. Of course, ACC drivers must devote some visual surveillance in support of lane-keeping, but rather long lapses in attention to the

outside scene can be tolerated while still holding one's nominal position within a lane. Moreover, such a reductive error would jeopardize driving safety by inducing inattention to the host of crash threats that might emerge from something other than (a) the preceding vehicle and (b) one's position in the lane. Included in this group are such hazards as halted traffic up ahead, traffic signals, pedestrians, construction crews and equipment, animals, road junk, or a loss of control or other dramatic maneuver by vehicles in adjacent lanes.

Moreover, the projections of very long travel distances between necessary interventions are believed to speak to a potential safety issue vis-à-vis human vigilance performance, under ACC control. Although these data are not conclusive, they call for searching out the signs of driver vigilance, or the lack thereof, during naturalistic tests of ACC-equipped vehicles. Noting that most ACC products seem to be targeting deceleration authority levels that are near or above 0.2 g's, there is good reason to believe that vigilance during the long periods between necessary interventions will have some impact on both the ACC intervention behavior of individuals and their attentiveness to other driving hazards.

6.0 Special Contributions of the FOCAS Program

This section pertains to the evolution of increasingly capable and driver-acceptable adaptive cruise control (ACC) and forward collision-warning (FCW) systems. It emphasizes advances in conceptual reasoning pertaining to the development of driver assistance systems. Special contributions of the FOCAS program towards a more complete understanding of manual, automated, and driver-assisted control of speed and distance are summarized here.

6.1 Virtues of Cooperative Agreements

At the beginning of this summary, it is important to recognize that the FOCAS program was conducted under a cooperative agreement. This agreement was between the United States Department of Transportation's NHTSA and the University of Michigan's UMTRI. The industrial partners to the agreement were ADC and Conti-Teves. Other partners assisting in the program were the State of Michigan and Haugen and Associates. Each of these entities brought special skills and perspectives to the program. Without the contributions of each of these entities, progress would have been much slower and the chance of success would have been much less.

The nature of the cooperative agreement provided the flexibility needed to address technical and system issues in a timely manner. In this arrangement, we were able to create new prototypical systems, thereby providing the means for studying the properties of new driver assistance functions. We could be both scientists and engineers in the sense that "scientists study what is, whereas engineers create what never was."[32] This cooperative agreement provided the environment needed to conduct forward looking research aimed at improving highway transportation and at aiding in the design of human-centered driver assistance systems.

6.2 Evolution of a Hierarchical Approach to System Development

By the end of the program, we had designed a number of ACC and FCW systems. We carried some of these designs through to physical realizations of working ACC and FCW systems. In addition, the designs of certain FCW systems were evaluated by having them operate on data that had been gathered during manual driving on freeways. The point is that, based upon this experience, a hierarchy of design considerations evolved.

Figure 80 illustrates the elements of this hierarchy. The elements shown in the figure are arranged according to the level of abstraction involved. For example, the "functional purpose" of the system is at the highest level of abstraction, in the sense that this element is the furthest removed from a real, physical device. The physical device (or system or process) is represented by "physical form" shown at the bottom of the hierarchy in Figure 80. Clearly, the physical device is intended to perform in accordance with the functional purpose of the system.

FROM GOALS TO REALITY AND BACK

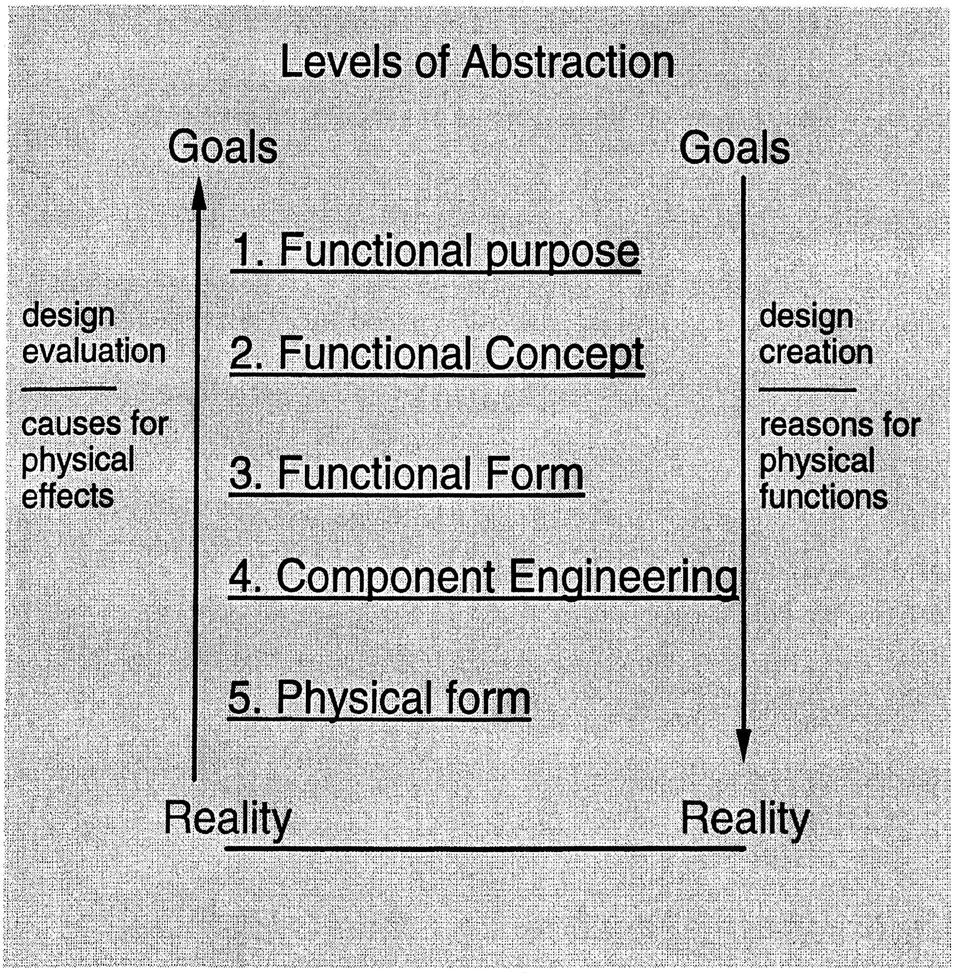


Figure 80. Design considerations

The elements between "functional purpose' and "physical form" need to be handled well for the system to work satisfactorily. In creating the design, the steps between levels are based upon reasons for physical functions. Although there could be many design realizations based upon the functional purpose of the system, each individual realization depends on its own set of reasons concerning the concepts and components utilized in developing that particular system. The creative step needed to design a new system has been described as follows. "An invention is related to a jump of insight which happens when one mental structure upwards from physical form and another downward from functional meaning, which have previously been totally unconnected, suddenly merge to a unified description."[30] This jump of insight is the essence of element 3, which is labeled "Functional form." The idea behind this element is that function fits form and form fits function. This is where the design becomes unified.

Once we have engineered a system, we are in a position to evaluate it. The evaluation process involves the same elements as the design process. However, in evaluation, we are looking for causes for physical effects. (In the design process, we were looking for reasons for physical functions.) In a sense, evaluation is like troubleshooting. We are seeing if there are problems—are the effects observed in accordance with the causes intended? If the evaluation at the highest level of abstraction shows that the system performs in accordance with its functional purpose, there is proof of concept. Evaluation at lower levels involves greater attention to detail and opens possibilities for discovering areas needing improvement.

In the FOCAS program, we created and evaluated designs of three different ACC systems. The first system had a fixed-beam sensor and its physical realization was in a SAAB 9000 automobile. The second system employed a sensor with a steered beam. It employed transmission downshifting. It was installed in a Chrysler Concorde. (This design was used in the ICC FOT, whereby ten identical vehicle systems of this type were built and employed by laypersons.) The third system had enhancements added to the second system. These enhancements included a smart booster, which accepted braking commands from a braking algorithm created in the FOCAS program. In hindsight, we see that we addressed each of the five elements shown in Figure 80 each time we developed a new ACC system. We recommend the use of a construct like Figure 80 as guidance for the conceptual reasoning associated with creating and evaluating designs of driver assistance systems.

The ideas behind Figure 80 are very important to the system integrator. (UMTRI was the system integrator for the FOCAS program.) We observe that vehicle manufacturing organizations also use a process similar to that indicated in Figure 80 in their development programs. When there is a general understanding of the elements involved in creating and evaluating a design, the partners to a cooperative agreement are in a good position for establishing a strong working relationship.

6.3 Analogy, Abstraction, and Aggregation in the Development of Human-Centered Designs

In the FOCAS program, we have found that strategies involving analogy, abstraction, and aggregation are effective in understanding and representing the complex environment associated with driving.

One of our underlying goals throughout the program was to compare ACC driving and forward collision-warning concepts with manual control and driving. This goal was based upon the idea that manual driving could serve as an analogy for which speed and distance control solutions were already known. As it turned out, we needed to depend upon measurements of range and range-rate made during manual driving. The sensors incorporated in the ACC-equipped vehicles provided the means for making these measurements. In this way, the FOCAS program provided an important database concerning manual driving.

Furthermore, these data on manual driving have been examined carefully and analyzed to produce a basic understanding of a theory of driving. This is where aggregation and abstraction played an important role. Histograms and cumulative distributions of the frequencies of occurrence of critical variables were used extensively to condense data gathered in the form of long time histories. These processed data were used to discover and extract chunks of knowledge concerning how people drive vehicles. As familiarity with basic aspects of driving behavior increased, researchers were able to develop mathematical relationships describing the phenomena observed. The abstractions represented by these mathematical formulas have played a significant role in the FOCAS program. They provide the basis for extending conceptual reasoning from a largely qualitative enterprise into a quantitative process. Further evolution of the application of the theory of driving to the design and evaluation process will benefit from the development of improved abstract models of the driving process.

At the beginning of the FOCAS program, we did not have an applicable understanding of what drivers do with regard to controlling speed and distance. Now we have advanced to the point where this report provides an initial set of answers to the following engineering questions pertaining to, especially, the longitudinal control aspects of manual driving:

• What is happening in manual driving?

• How does it work?

• How can this knowledge be used?

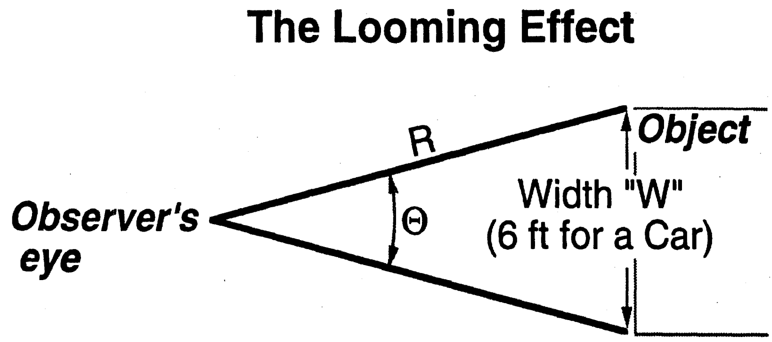
Throughout the program, we have addressed these questions in the context of comparing ACC driving to manual driving. In this regard, measurements of manual driving performance have been made whenever measurements of ACC driving were made. We recommend this procedure involving measurement because the theory of driving is not yet advanced enough to rely solely upon predictions made using theoretical constructs or models.

Nevertheless, the formulations of models of driver behavior constitute valuable steps in the development of a theory of driving. The researchers in the FOCAS program have produced numerous technical papers, based upon FOCAS results. These papers have contributed to the development of pertinent and applicable driver models [5 through 10].

6.3.1 Creation and evaluation of human-centered designs: perception

The development of a database and an understanding of driver behavior in manual driving were fundamental to the creation and design of human-centered driver assistance systems. To be human centered, driver assistance systems need to match the physical and mental capabilities of drivers.

One pertinent aspect of driver capabilities has to do with the perceptual abilities of drivers. In this regard, the looming effect (illustrated in Figure 81) has played a central role in the FOCAS program.



$$W = R \bullet \Theta$$

$$0 = Rdot \bullet \Theta + R \bullet \Theta dot \quad \text{or} \quad \frac{R}{-Rdot} = \frac{\Theta}{\Theta dot}$$

Figure 81. Illustration of the looming effect

As indicated by the equations presented in the figure, the size of the image projected onto the eye depends upon the range to the observed object. If there is relative motion between the observer and the object, the range is changing (that is, range-rate is not zero). As indicated in Figure 81, the rate of change of range is related to the rate of change of the angle occluded by the image as projected onto the eye. In this context, the looming effect is represented by the ratio of occluded angle (image size) to the rate of change of that occluded angle (that is, θ/θdot). As shown by the equations in the figure, the looming effect as represented by θ/θdot is equal to the time-to-impact, which is represented by (R/-Rdot). In other words, the driver's sensation of looming has a direct interpretation in terms of range and range-rate, which are the quantities measured by the sensor employed in ACC systems. In this sense, there is an analogy between what the person perceives and what the sensor measures.

If the object is moving, the ratio (R/-Rdot) is called the time-to-impact (when Rdot is less than zero). However, if the object is a stationary object at range R and the observer in the vehicle is moving at velocity V, Rdot is negative and is equal in magnitude to V. In this situation, the looming effect (θ/θdot) for the stationary object is equal to R/V, which is called the headway-time-margin in this report.

The desired value of headway-time-margin has been used extensively in expressing the driver's objective when the driving situation warrants following another vehicle. The ACC systems developed in the FOCAS program evolved to include a design feature providing drivers with a set of choices (allowing more than one value) of the desired headway time. The desired headway time is called the time headway and it is represented by the symbol Th to distinguish it from the existing value of headway-time-margin symbolized by Htm.

In ACC driving, the difference between Htm and Th represents a measure of how far the current driving situation differs from the driver's desired headway time. This difference has played an important role in both the designs of the control algorithms used in ACC systems and the designs of the controls available to the driver for adjusting the characteristics of the ACC system. The findings from the FOCAS program show that driver age has a major influence on the time headway chosen by a particular driver. We believe that a set of headway time settings covering from 1.0 to 2.0 seconds is a reasonable choice of settings. This provides for meeting human-centered considerations related to driver comfort and convenience as well as those related to providing a safety margin for the alert driver to use in reacting to unexpected events.

With regard to time-to-impact, the ACC systems developed in FOCAS did not allow the driver a choice of closing rate. However, the closing rate used in the ACC systems was based on considerations of the rates of closure that would be acceptable to drivers. Although detailed theoretical knowledge is yet to be discovered, the experience from the FOCAS program indicates that closure to the desired time headway with a time constant of approximately 10 to 12 seconds appears to be satisfactory. Drivers seldom closed on a moving preceding vehicle with a time constant less than 5 seconds. Closing sequences involving time constants approaching 5 s are believed to result simply from the driving situations and thus do not appear to be dictated by driver preferences. Observations suggest that drivers appear to become anxious when the time-to-impact (Tti) falls below 9 or 10 seconds. When this happens, drivers are likely to apply the brakes.

The time-to-impact has often been used in the past in studying situations involving intersections and/or stopped objects. These situations are different than slowing to the speed of a preceding (impeding) vehicle. However, if the impeding vehicle is stopping or already stopped, the driver may switch to a different set of tactics appropriate for dealing with stopping situations.

The designs of the braking algorithms used in the FOCAS program have included features representing compromises involving a number of issues. These issues include limiting the jerk and deceleration experienced by the driver to be compatible with the severity of the current driving environment and responding to sudden merges and deceleration events by braking in a timely manner. In addition, forward collision-warning features have been considered with regard to the need for emergency braking as well as the need for informing the driver when the driver is in a situation that would ordinarily call for braking.

The FOCAS program has contributed knowledge and concepts that will aid in the resolution of the issues associated with ACC braking. Manual driving data is now available for use in examining how ACC-with-braking and FCW systems operate. Preliminary concepts have been developed to aid in understanding when drivers decide to brake. Nevertheless, the understanding of appropriate responses of drivers and driver assistance systems in situations requiring hard braking is not well developed. Research involving further on-road study of the designs examined in this study is recommended. In addition, the creation of new designs and their evaluation is desirable. The development of new systems can play an important role in the evolution of acceptable and effective systems that will assist the driver.

It is believed that drivers also perceive their speed by means of the visual streaming effect involving the texture of the passing road features in the near environment. Although this effect was simply accepted as being present in the FOCAS program, it played an important conceptual role in the approach to driver modeling and conceptual reasoning used in the program. The combination of velocity (V) with time-to-collision (R/-Rdot) and headway-time-margin (R/V) provides information that is equivalent to that provided by the sensors in an ACC and/or FCW equipped-vehicle. The results of the FOCAS study indicate that measurements of range, range-rate, and velocity (or equivalent perceptions) can provide basic information as needed for satisfactorily controlling speed and distance in highway driving.

6.3.2 Creation and evaluation: decision, command, and control functions

The driver has two roles in controlling the driving process. As described in the previous section, the driver needs to perceive the state of the driving environment, especially with regard to impeding vehicles. The second role of the driver is to manipulate the vehicle's controls in a manner that satisfies the driver's objectives. That is the subject of this section.

In the context of human-centered design, the ACC and FCW systems developed in FOCAS involve an analogy between certain concepts derived from nonlinear control theory [29] and certain concepts pertaining to human performance models [30].

Figure 82 illustrates the interconnection of various psychological processes associated with the driving process. In this depiction of the driving process, the principal elements are the driving situation, signal processing (as performed by the driver's perceptual skills), the vehicle, and three elements labeled “”knowledge”, “rules”, and “skills.” The evolution of the ACC designs created in the FOCAS program is related to the properties of the knowledge, rules and skills elements as presented next.

Psychological Concepts in the Driving Process

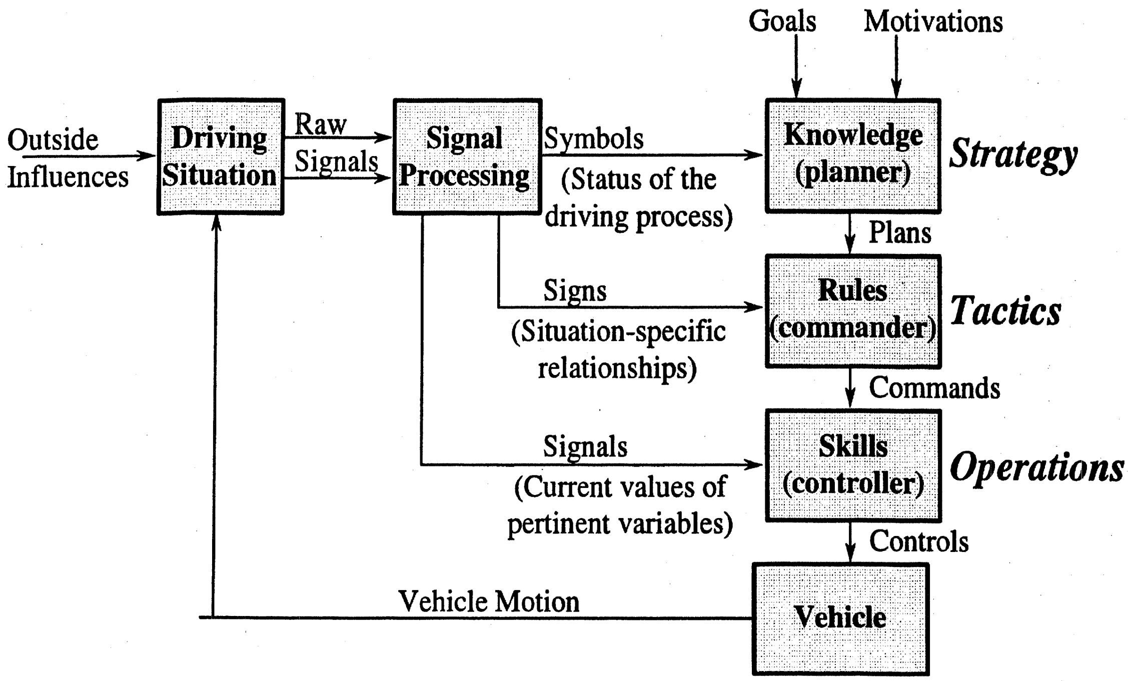


Figure 82. Psychological concepts in the driving process

As indicated in Figure 82, knowledge is associated with overall strategy concerning the status of the driving process. Rules involve situation-specific relationships. There are different rules (tactics) for different situations. Skills are associated with routine operations learned through experience. This is where perceptual-motor skills occur—involving nearly raw signals that pass from the eye to the foot with almost no cognitive recognition in the mind.

The knowledge, rules, and skills elements receive separate types of inputs from the signal-processing element. The distinctions between the natures of these inputs (symbols, signs, and signals) are important to the creation and evaluation of human-centered designs of ACC and FCW systems. These distinctions have a psychological basis [30]. The following discussion is directed at the interpretation of signals, signs, and symbols in the context of the design and evaluation procedures used in the FOCAS program.

Signals are basically time histories of pertinent variables as measured by the sensors (R, Rdot, and V). Relationships between these variables, including quantities such as time-to-impact and headway-time-margin, are used to classify driving rules into learned patterns or, if needs be, into new rules created at the knowledge level. The decision as to which rule to use is expressed in terms of mathematical inequalities in the algorithms developed in the FOCAS program. These inequalities are the basis for the signs indicated in Figure 82. Each rule is expressed by mathematical formulae describing the actions applied to the vehicle's controls. Hence, if familiar signs are present in a driving situation, the driver (or the system) knows what to do. If situations arise for which driver skill and experience are of little avail, the knowledge element uses symbols received from the signal-processing unit to determine a suitable course of action. These symbols pertain to high levels of cognition such as would feed a mental model. They are tied to functional properties, and they can be used for conceptual reasoning.

In a sense, current ACC systems or FCW systems are not very intelligent. The knowledge element exists in the mind of the designer of the system and, hence, it does not travel along in the equipped vehicle. For this reason, there is a practical need for the human driver to be prepared to supervise the ACC system.

The driver notices aspects of the driving situation that the sensors do not measure. The system is not aware of the driver's goals such as those associated with navigation or position within a traffic stream. (In a sense, the system has some knowledge of the driver's higher-level thinking through the headway time setting and the set-speed value that is chosen by the driver. Also, the system knows whether the driver is overriding with the accelerator pedal or intervening with the brake pedal.) The system does not know speed and distance control matters associated with passing another vehicle or preventing a vehicle from an adjacent lane from cutting in, for example.

In addition, the systems have only limited control authority because one does not want a false or incomplete set of measurements to trigger a sudden, rapid deceleration that might be a significant traffic hazard. Based upon considerations of this type, the ACC-with-braking system developed in the FOCAS program had a maximum deceleration authority of 0.22 g. Currently, there is considerable debate concerning the proper choice of maximum deceleration authority. The researchers in the FOCAS program have argued for lower and higher levels of deceleration authority. Matters such as vigilance and the impact on the predicted safety record have been examined. Although useful ideas and results have been developed, we do not believe that a satisfactory resolution to the question of maximum deceleration authority has been achieved.

The ultimate test may be the accident experience of the initial offerings of these systems. The combination of ACC and FCW systems may eventually prove to be beneficial in reducing the accident risks to a level that is better than that associated with manual driving now. Regardless of the exact level of control authority employed in these systems, one could argue that driving with ACC will be safer than manual driving, at least in part because people appear to avoid using ACC systems when the driving situation is difficult or risky.

Returning to the meaning of Figure 82, the portrayed concepts have been translated into a more conventional type of block diagram associated with the flow of information used in the design of an ACC system. See Figure 83. This diagram was constructed with manual driving in mind. The intention is that the concepts used in the ACC system will be analogous (or at least relatable) to those used in manual driving.

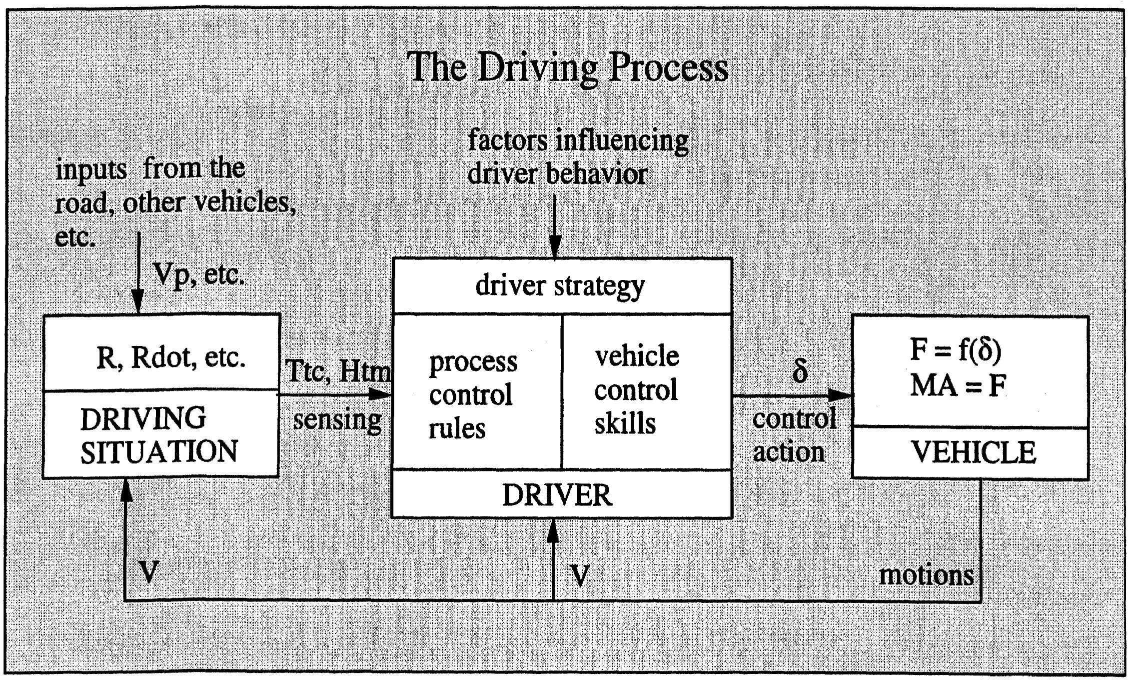
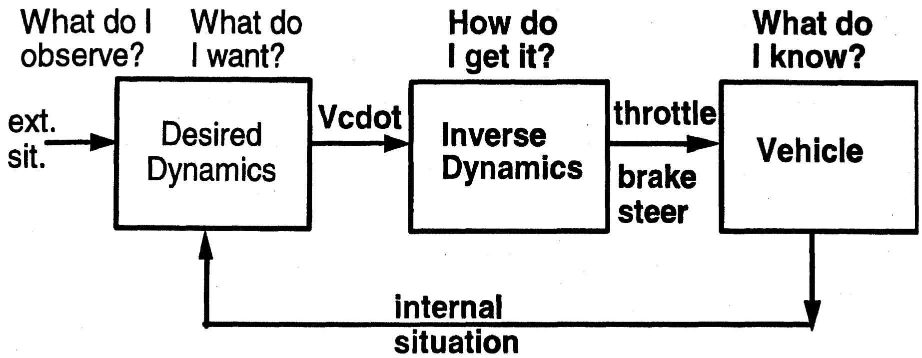


Figure 83. Functional diagram describing the driving process

The driver is the central element in Figure 83. The driver (or a driver-assistance ACC system) receives signals and signs from sensory units. In this diagram, symbols and knowledge related strategy are not emphasized. Cognitive processes are represented simply as strategic factors such as those associated with being in a hurry or wanting to keep a small gap to the preceding vehicle. In this conceptual model of the driving process, the driver translates sensory information into signs for selecting process-control rules and signals for use in the application of vehicle control skills.

Figure 84 illustrates the concept developed in FOCAS for representing and modeling driver or system control actions. The control actions derive from the use of the so-called "inverse dynamics" of the vehicle. This is simply an approximate inverse of the system of equations describing the vehicle. As indicated by the set of equations shown in Figure 84, the throttle or brake control applied to the vehicle is based upon the inverse dynamics of the vehicle. When this condition is satisfied, the velocity of the vehicle will be as intended by the driver or the controller. This means that the velocity will be the integral of the acceleration command Vcdot, which is based upon the desired dynamics chosen for the entire driving process including the input from the driving situation. (The generation of Vcdot will be discussed in connection with the next figure.)



F(**Control**) = M Vdot + Fd

Control = F^{-1}(M Vdot + Fd)

But if **Control** = F^{-1}(M Vcdot + Fd),

V = ∫ **Vcdot** dt, which is what we want.

Figure 84. The meaning of inverse dynamics

The feed-forward control shown here as inverse dynamics can also be arranged as a feedback control system. In order to make a simple prototype ACC system, the set-speed in the conventional cruise control system was used to perform the inverse dynamics function for throttle modulation in the FOCAS program.

Figure 85 shows examples of the types of inverse dynamics formulas that are pertinent to ACC systems with braking. The quantity, Fd, represents an estimate of the drag forces acting on the vehicle. There are separate formulas for involving either throttle or brake control. The properties of the drive train and the engine are represented by the inverse function for the acceleration force, Fa. Similarly, the braking pressure is represented by the inverse of the function for braking force, Fb. An inverse dynamic function for Fb (like that shown in Figure 85) was utilized in the ACC-with-braking system created in the FOCAS program. We believe that using an inverse function for the throttle control would have had superior performance over that provided by using the velocity control system developed by the OEM for conventional cruise control purposes. However, the FOCAS results indicate that drivers liked the FOCAS ACC systems. These systems received high subjective ratings concerning comfort, convenience, and driving enjoyment.

Vehicle Dynamics

$$m\, dV/dt = Fa - Fb - Fd$$

Throttle Inverse Dynamics

$$\delta = Fa^{-1}[m\ VcDot + Fd]$$

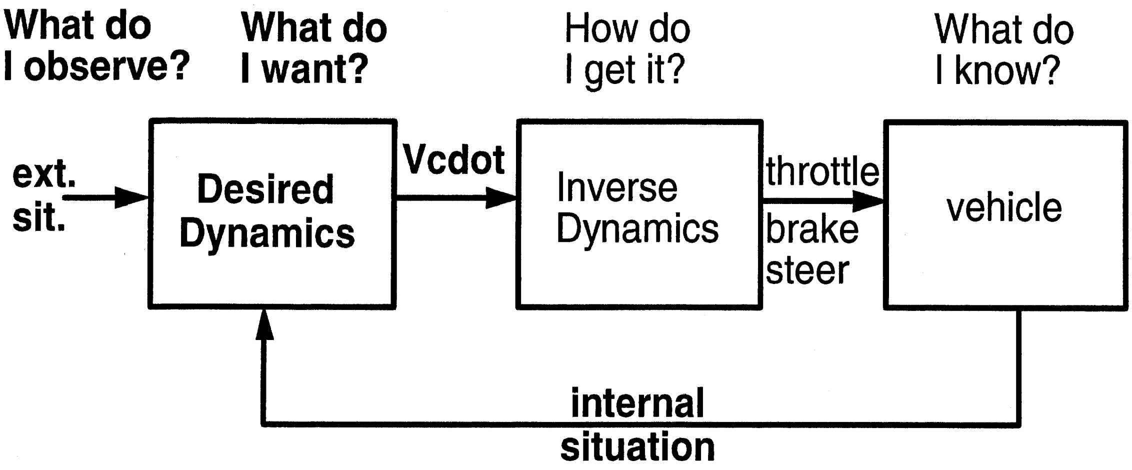
Brake Inverse Dynamics

$$Pb = Fb^{-1}[-m\ VcDot - Fd]$$

Figure 85. Example illustration of inverse dynamic formulas

The inverse dynamics approach described here is related to a concept known as feedback linearization in nonlinear control theory [29]. It is part of a method for using a known entity (such as the vehicle) to obtain a desired set of dynamics for the driving process as a whole. The inverse dynamics feature is useful in that it provides a separation between considerations involving knowledge of the vehicle's dynamics and considerations involving the appropriate reaction to the current driving situation. In this manner, the design process can be viewed in two separate but complementary steps. One step, involving inverse dynamics, is based upon knowing how the vehicle responds to control inputs. (An experienced driver is regarded as having learned how the vehicle will respond to control inputs.) The other step, described next, involves deciding on an appropriate course of action given information concerning the current driving situation.

Figure 86 illustrates the formulae used in explaining how a driver or a system develops process dynamics that will lead to a desired headway range (Rh). The approach, outlined by the equations in Figure 86, involves what is called a control objective function. If the process is performing in accordance with the control objective function, the error is zero. The system is said to slide along the surface defined by the control objective function. If the error (e) is not zero, a control rule is devised to force the error towards zero. In the FOCAS work on ACC, a simple first-order system was found to do a satisfactory job of controlling the desired dynamics of the process yielding, as discussed before, high subjective ratings from lay drivers. These systems used time constants (T), which were around 11 seconds, and Rh was in the range from 1 to 2 seconds times the velocity (V) of the equipped vehicle. These values were compatible with manual-driving performance as measured in the FOCAS program.



Desired Dynamics reasoning:

T Rdot + R = Rh, Rdot = **Vp** - **V**,

T Rdot + R - Rh = e,

edot + e/Te =0

Vcdot = Vpdot + (Rdot -Rhdot + e/Te)(1/T)

Figure 86. Desired dynamics of the driving process

Figure 87 illustrates that other forms of acceleration command are readily derived using the desired dynamics approach. In this case, the control objective function is simply one involving the desire to make the headway-time-margin (R/V) equal to the time headway (Th) set by the driver. (In other words, the control objective function is R/V –Th = 0 and the error is given by e = R/V-Th.) In addition to consideration as the basis for an ACC-control algorithm, the equation for Vcdot given in Figure 87 was used as the basis for a collision-warning algorithm in the FOCAS program. If the calculated value of Vcdot was less than a selected threshold value, an FCW alert was issued to the driver in either ACC or manual driving. In this sense, both the ACC algorithm and the FCW algorithm are based on the belief that there is a human-centered desire to achieve a pre-selected headway time.

Driver Acceleration Command

Desired Dynamics:

$$e = R/V - Th$$

$$T\, de/dt + e = 0$$

Command:

$$dV/dt = (V/R)\left(dR/dt + \frac{(R - Th\,V)}{T}\right)$$

This means dV/dt = VcDot for emulating driver behavior

Figure 87. An example of an alternative acceleration command

6.4 Range Versus Range-rate as an Indication of Proof-of-Concept.

Figure 88 is a generic diagram portraying the space of output values available from an ACC and/or FCW sensor.

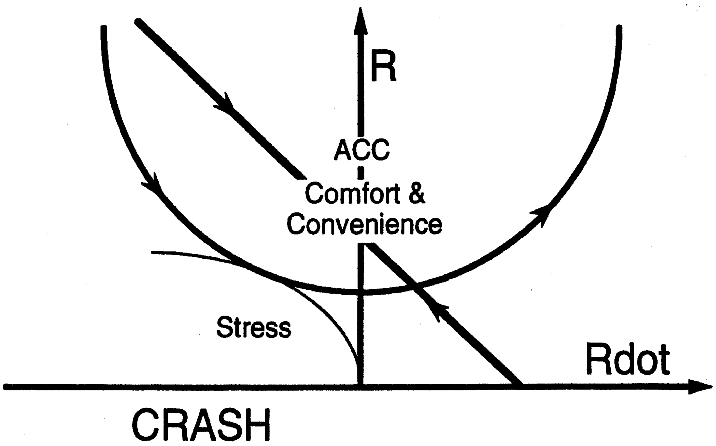


Figure 88. An annotated range versus range-rate diagram

The diagonal line from upper left to lower right represents a desired dynamics line (the sliding surface chosen as a control objective function). The curved parabolic line represents a constant deceleration trajectory intercepting the range axis at a desired value of headway range in this diagram. The mathematical details associated with this phase space were analyzed and described in the early days of the FOCAS program [31]. The concepts and design procedures described in [31] are still pertinent today.

As a result of our appreciation for the power of the range versus range-rate display, we decided to make two dimensional histograms to display the frequency of driving occurrences in bins representing various levels of range and range-rate. These diagrams (see Figure 18) have become prima facie evidence as to whether an ACC system satisfies its functional purpose of achieving a desired time headway. This type of display, showing side-by-side plots of ACC and manual driving in similar circumstances, is recommended for use in deciding at the highest level of abstraction whether the operation of an ACC system is basically satisfactory.

6.5 Supervision of Speed and Distance Control

When driving with ACC, the driver has a new task to perform. The driver is responsible for making sure that the driving situation is safe, while not actually exercising control over longitudinal motion. The instructions given to lay drivers in the FOCAS program includes the admonition, "If it looks like you need to brake, then brake." Figure 89 provides a conceptual overview of the driver's supervisory role.

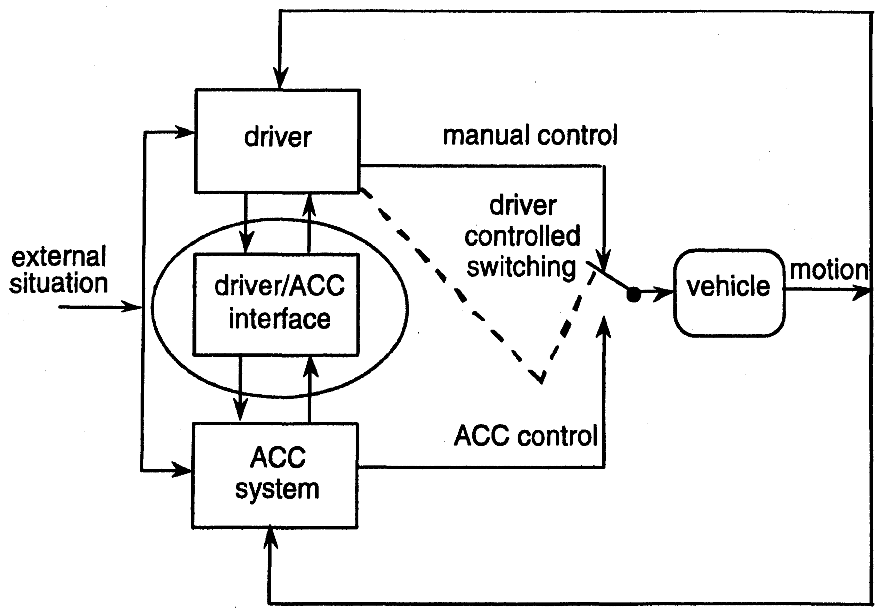


Figure 89. Overview of control supervision

This role involves some surprising features. Since driving is mainly a perceptual-motor skill, the uninitiated driver can be surprised when the ACC-equipped vehicle slows without the driver doing anything. Even more disconcerting in the long run is the tendency of drivers to expect the ACC vehicle to slow when they would have, if operating under manual control. Drivers appear to develop a fine sense of when to coast, often seeming to be cognitively unaware that they are coasting. In manual driving, there appears to be much throttle modulation that is done automatically by the driver without awareness of it. Due to these kinds of effects, drivers need to develop a feeling for how the ACC system operates. They need to develop skills, rules, and knowledge to use in deciding whether to intervene on ACC operation.

No one knows how driver supervision processes will develop when ACC products are used in large numbers. However, there are concerns that drivers will become too complacent if the ACC system appears to solve many of the speed and distance control problems encountered by the driver. The driver may come to depend excessively upon the system so as to lapse in the level of vigilance needed to maintain a satisfactory level of situation awareness. The matter of vigilance and the influence of deceleration authority on the frequency of the need to intervene on ACC driving were given special attention in the final year of the FOCAS program. The results are very interesting and they indicate that long periods of highway driving will transpire between intervention events, especially for an ACC system having greater than 0.2 g of deceleration authority. On the other hand, drivers have many discretionary reasons for intervening on ACC driving. In addition, they will still need to exercise visual surveillance in order to steer the vehicle (at least until path-keeping systems come along). The net result at this time is not clear. Perhaps the issue of vigilance will not be resolved until the quantity of naturalistic data on actual driving reaches levels needed to support epidemiological studies.

6.6 Safety Concepts

One approach to envisioning the world of safety countermeasures is to consider the ICE cube presented in Figure 90. The idea of this cube is to start with the risk of exposure to dangerous situations, then proceed to the risk of a crash given exposure to risky situations, then consider the probability of injury and the severity of that injury, given a crash. Interestingly, ACC systems have the potential to shrink the dimensions along all coordinates of the ICE cube, thereby significantly reducing the volume of the cube and greatly reducing the magnitude of the speed and distance control problem. In other words, ACC systems have the potential to reduce the number and severity of rear end crashes.

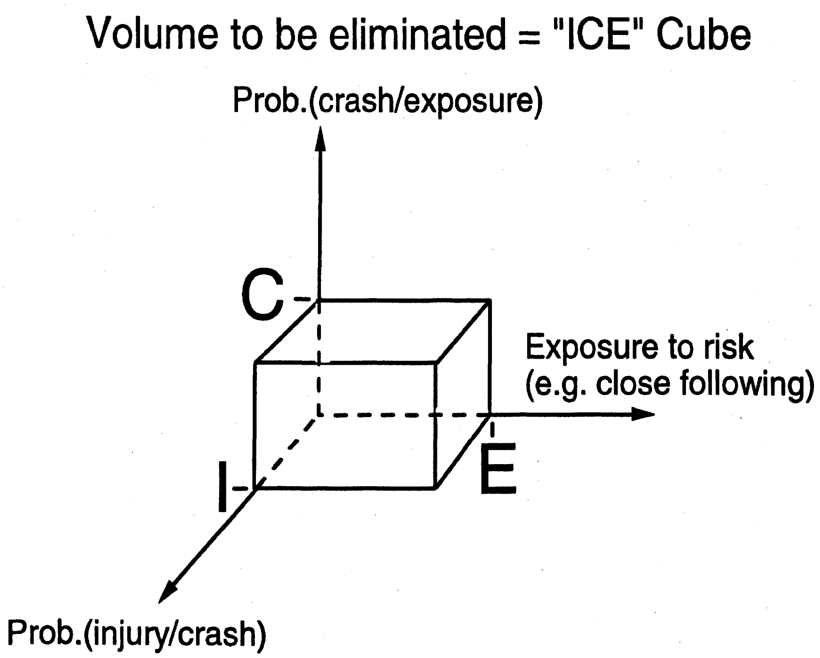


Figure 90. Safety concepts represented in the ICE cube

The basic functional purpose of the ACC system is to maintain pre-selected headway times. The results of the FOCAS study indicate that ACC systems can be expected to provide longer times for reacting to changes in the driving situation than the reaction-time safety factors that drivers provide when driving manually. In this sense, the ACC system reduces the incidence of following too close.

In the event that the preceding vehicle slows rapidly or appears suddenly in the path of the equipped vehicle, the ACC system will respond quickly, initiating corrective action sooner than drivers would typically respond. This can reduce the probability of a crash given the exposure to these types of risky situations.

Furthermore, even if a crash ensues, the braking action of the ACC system will reduce the speed of the equipped vehicle at impact—even if the driver does nothing, as often appears to have been the case in many rear-end accident studies. This result will reduce the severity of the crash and the rate of fatalities, as well.

In addition, if an FCW system is included with the ACC system, one would expect that drivers will be prompted into action when the driving situation warrants rapid and effective braking.

All of these benefits depend upon a number of practical considerations. Many of these practical matters involve whether the drivers will understand how ACC systems function. Will drivers know what ACC systems can be expected to do for them? Goals of human-centered design are to keep the driver involved in the driving process and aware of the driving situation. If the actions of the system are tailored to the mental and physical capabilities of drivers, there is hope that the drivers will make wise use of the capabilities of ACC vehicles. Whether this can be achieved such that both the driver and the ACC system are working together to prevent crashes is the ultimate question.

The efforts in the FOCAS program have been directed at developing comfortable and convenient ACC systems that do not compromise safety. Nevertheless, the ideas and concepts that have evolved from the FOCAS program have not all been challenged in naturalistic driving by lay people satisfying their transportation needs and desires. The performance of these driver-assistance systems needs to be studied in the context of typical transportation service. Even beyond that, the resolution of safety issues may not be resolved or even recognized until many ACC products are commercially available and people have had a chance to use them for a year or more. Even so, the potential promise offered by ACC systems makes them a good candidate for serving the nation's interest in highway safety.

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APPENDIX A
INFORMATION LETTER — ACC WITH BRAKING STUDY

Dear Driver,

The University of Michigan Transportation Research Institute and the National Highway Traffic Safety Administration are conducting a study of new cruise control devices for passenger vehicles. One particular device is referred to as "adaptive cruise control." We are examining the impact of these devices on driving safety, comfort, and convenience. We are particularly interested in the design of adaptive cruise control. We believe this is important research that will contribute to enhancing automobile safety and comfort, but want to ensure that these devices are designed with the drivers' needs in mind.

You have been asked to participate in this study, and as such, you will be driving a research vehicle that is equipped with this new form of cruise control on public roadways.

During testing, an experimenter will always be present in the car with you. The experimenter will instruct you on where to drive, and ask you to use adaptive cruise control, conventional cruise control as well as to control the car manually. The experimenter will also be present to answer any questions you may have during the course of the study. As you drive, the experimenter will operate a computer that records specific information about how the car is being operated. In addition, a video camera will be used to record images of the road and other traffic near the experimental car. These video images will include comments you make about the way the car operates, but no pictures of you will be included in the video.

At no time during this study will you be asked to perform any unsafe driving actions. You must possess a valid, unrestricted, driver's license. You must have a minimum of two years driving experience. You must not be under the influence of alcohol, drugs, or any other substances which impair your ability to drive (recall that you were asked to refrain from the use of alcohol, drugs, or substances which impair their ability to drive for a period of no less than 12 hours prior to participating).

RISKS: While participating in this study, you will be subject to all the risks that are normally present when driving a passenger car on public roads. Use of the adaptive cruise control device being studied should not make driving any more hazardous than normal. However, caution should be used when operating a vehicle with which you are not familiar. The adaptive cruise control device you will be using will automatically accelerate and decelerate the test vehicle in order to maintain a set distance separation (headway) between the test car and other cars which you follow. It is the amount of deceleration, and when the deceleration begins, that is the focus of this study. The level of deceleration you may experience is comparable to that of modestly applying the car brakes.

Be aware that accidents can happen at any time when driving, and that you can not rely on any device being studied to prevent an accident. In the unlikely event that an accident occurred; you, the experimenter, the test vehicle, as well as any other persons or property involved, would be covered under an insurance policy held by The University of Michigan Transportation Research Institute and The University of Michigan.

BENEFITS: The results of this study will provide valuable guidance for the development of cruise control and braking systems for passenger cars. By participating in this study, you will be lending your experience and expertise to support highway safety research.

PAYMENT: You will be paid $30 for participating as a test driver in this study. Your participation in the study will require approximately three (3) hours.

CONFIDENTIALITY: The University of Michigan Transportation Research Institute and the National Highway Traffic Safety Administration are gathering information on the use of adaptive cruise control in passenger cars. We are not testing you or your skills. If you agree to participate in this study, your name will not be voluntarily released to anyone who does not work on this project. Your name will not appear in any reports or papers written about the project.

The University of Michigan Transportation Research Institute and the National Highway Traffic Safety Administration **hope** that you will agree to participate in this study. If you have any questions, please feel free at any time to ask the experimenter.

Once you have had your questions answered, please let the experimenter know whether you are interested in participating in this study. If you are willing to participate, the experimenter will ask you some questions to ensure that your skills and experience match our research needs. If it is determined that you qualify to participate, you will be asked to read and sign an Informed Consent Form before you can actually participate in the study.

APPENDIX B
INFORMED CONSENT FORM — ACC WITH BRAKING STUDY

I, ______________________________, agree to participate in The University of Michigan Transportation Research Institute's study of adaptive cruise control for passenger vehicles.

I understand that:

1. The purpose of this experiment is to investigate driver impressions and driving behavior concerning a new type of cruise control technology called adaptive cruise control.

2. As a test driver, I will drive an instrumented car which is equipped with this new cruise control technology on public roads.

   a. I will be asked to drive the research vehicle equipped with adaptive cruise control, and to experience the rate at which the system automatically slows the vehicle.

   b. At the conclusion of driving I will be asked to complete a questionnaire regarding my impressions of the adaptive cruise control system.

   c. A video camera will be used to record the traffic and roadway conditions during the study. My voice, but not my face, will be included on this video tape.

3. An experimenter will be present with me at all times. The experimenter will familiarize me with the adaptive cruise control device and the test vehicle in which it is installed.

4. The experimenter will provide me with specific instructions as to where I will be driving, ask me questions, operate measurement equipment in the test vehicle, and ensure that no inadvertent risks are taken.

5. At no time in this study will I be asked to perform any unsafe driving actions.

6. I agree to obey the instructions of the experimenter, in so far as I do not feel that I am driving in a manner that is not consistent with my regular driving habits.

7. I must possess a valid, unrestricted, driver's license.

8. I must have a minimum of two years driving experience.

9. I must not be under the influence of alcohol, drugs, or any other substances which may impair my ability to drive, and I have refrained from the use of such items for a period of at least 12 hours.

10. While driving in this study, I will be subject to all risks that are normally present while driving a passenger car on public roads. The use of adaptive cruise control is intended to make driving more comfortable. However, caution should be exercised when operating a vehicle with equipment with which one is not familiar. I understand that the adaptive cruise control device will automatically accelerate and decelerate the test vehicle in order to maintain a selected distance separation (headway) between the test car and any car I am following, and that the level of deceleration is comparable to that of moderately applying the car brakes. I will not become over reliant on the adaptive cruise control system, and I am aware that accidents can happen at any time while driving. I understand that the existence of an adaptive cruise control system on the test vehicle will not eliminate the possibility of an accident occurring.

11. In the unlikely event that an accident occurred; myself, the experimenter, the test vehicle, as well as any other persons or property involved, would be covered under an insurance policy held by The University of Michigan Transportation Research Institute and The University of Michigan.

12. The results of this study will provide the University of Michigan Transportation Research Institute with information for the development of future adaptive cruise control devices. By participating in this study, I am lending my experience and expertise as a driver to support safety research regarding the future use of adaptive cruise control systems in passenger cars. I understand that I will not be informed as to the results of this study.

13. I will be paid $30 for participating in this testing. I understand that participation in this experiment will take approximately three hours.

14. The University of Michigan Transportation Research Institute is gathering information on adaptive cruise control devices, and not testing me. My name will not be released to anyone who is not working on the project. My name will not appear in any reports or papers written about the project. It is possible that, should I be involved in an accident during testing, that The University of Michigan Transportation Research Institute will have to release data on my driving in response to a court order.

15. The experimenter, an employee of The University of Michigan Transportation Research Institute, will answer any questions that I may have about this study. The experimenter in charge of this testing is:

James R. Sayer, Ph.D.

The University of Michigan Transportation Research Institute

Human Factors Division

2901 Baxter Rd., Ann Arbor, MI 48109-2150

Phone: (734) 764-4158

16. If information becomes available which might reasonably be expected to affect my willingness to continue participating in this study, this information will be provided to me.

17. Participation in this study is voluntary. I understand that I may withdraw from this study at any time, and for any reason, without penalty. Should I withdraw, I will be paid in full regardless of reason for withdrawal.

I, ______________________________, HAVE READ AND UNDERSTAND THE TERMS OF THIS AGREEMENT. I VOLUNTARILY CONSENT TO PARTICIPATE IN THIS STUDY.

______________________	______________________	______/______/______
Name (Print)	Signature	Date

______________________________	_(____)______________________
Address	Telephone Number

APPENDIX C
TEST PROCEDURES

Proving-ground tests were aimed at characterizing certain aspects of manual driving, and then to expose the participants to two automatic headway-control systems: one that is based on their own individual driving behavior, and another that is more of a standardized, benchmark system. Testing sequence was as follows: (1) measure headway time, (2) test-set one: characterize closing from long range, (3) test-set two: lead vehicle brakes, and (4) ACC driving. This appendix provides detailed procedures of each testing step.

The following terms and definitions are used in describing the test procedures:

- FOT car — an ACC-equipped vehicle without the capability of automatic braking
- ITT car — an ACC equipped vehicle with the capability of automatic braking
- Vset — the cruise control set speed
- driver — the participating test subject
- researcher

Measure Headway Time (Th)

The ITT car was driven by a researcher twice around the track (Vset=46mph during the1st lap, and Vset=60mph 2nd lap); the driver operated the FOT car manually so that it followed the ITT car. The driver was instructed to keep a constant headway (per his/her preferences) for each lap.

Processing: (1) select the data where the velocities are approximately constant

(2) compute T_h by:

$$T_h = mean\left[\frac{R}{V_{FOT}}\right] \quad (C1)$$

Test-Set One: Closing From Long Range

The researcher accelerated the ITT car to open a large gap from the FOT car (operated by the driver), and when he arrived at the start of the straightaway section of the track, he braked and quickly established Vset=46mph. The FOT car approached from behind with its cruise control set at Vset=60mph; the run terminated when the driver intervened by braking. This exercise was repeated three more times for a total of four closing-from-long-range sessions. However, during the last 3 sessions, the cruise speed of 46mph is established by using the "resume" instead of "set" button.

Processing: (1) select continuos data streams from just before braking, to just after transitioning from range rate < 0 to range rate > 0.

(2) compute looming coefficient, *K*, from equation (xx4)

(3) determine intercept range

(4) compute average deceleration (twice) from the start of brake application to the point when the range axis is crossed:

$$a_1 = \frac{V_{(\text{at intercept range})} - V_{(\text{at brake application})}}{\Delta T_{(\text{from brake application to intercept range})}} \qquad \text{(xxC2)}$$

$$a_2 = \frac{\dot{R}_{(\text{at brake application})}}{2 \cdot (R_{(\text{at brake application})} - R_{(\text{intercept})})} \qquad \text{(xxC3)}$$

(5) compute statistics (i.e., mean, standard deviation) for these parameters

Test-Set Two: Lead Vehicle Brakes

This test employed a special-purpose algorithm for an accurate and repetitive brake application. The set started with the researcher driving the ITT car (Vset=60mph) so that the FOT car with the driver followed behind at the same speed (under cruise control). About mid-length of the straightaway section, the special algorithm at the ITT car was activated to generate a deceleration level of 0.15 g. The run terminated when the driver intervened by braking. This exercise was repeated three more times for a total of four lead-vehicle-braking sessions.

Processing: (1) through (5) are same as for test-set one

(6) use judgement to select looming coefficient and intercept range parameters to be used in the "Personalized model"

ACC Driving

This sequence of tests involved two control algorithms: (1) a standardized benchmark ("the UMTRI algorithm"), and (2) personalized driver model (see discussion in section 4.0 of the report). In both algorithms the driver's preferred headway-time gap (as derived from the first suite of tests) was used. However, in the benchmark controller, headway time was the only parameters that was adjusted. In the personalized model, the looming factor, the minimum intercept range, and the deceleration level were also adjusted to represent the individual's driving preferences.

For each algorithm, the driver operated the ITT car (under ACC), now behind the FOT car (operated by the researcher), and repeated the testing suits test-set one and test-set two. No numerical data were collected during this step, however, at its conclusion the drivers were asked to fill questionnaires to describe their experience.

APPENDIX D

YEAR 5 DRIVER QUESTIONNAIRE AND SUMMARY STATISTICS

This appendix contains the year five subject questionnaire consisting of 43 questions. Four of the questions were of the free response form and the remaining 39 questions employed Likert-type scales ranging from 1 to 7. The mean and standard deviation for the Likert-type is given for each corresponding question.

Participant #________

Date ________

Adaptive Cruise Control System

Questionnaire and Evaluation

Please answer the following 43 questions. If you need to, you may include comments alongside the questions to clarify your responses.

Examples:

A.) Strawberry ice cream is better than chocolate?

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

You would circle the "1" if you really liked chocolate ice cream, or you might really like strawberry ice cream. In which case you would circle the "7."

1. How comfortable did you feel driving the car using the ACC system?

1	2	3	4	5	6	7
Very Uncomfortable						Very Comfortable

Mean = 5.8

Stdev = 1.2

2. How easy did you find it was to drive using the ACC system?

1	2	3	4	5	6	7
Very Difficult						Very Easy

Mean = 6.4

Stdev = 0.6

Briefly describe the types of situations or driving environments where ACC was easiest to use:

3. How likely is it that you would have become more comfortable using the ACC system given more time?

1	2	3	4	5	6	7
Very Unlikely						Very Likely

Mean = 6.3

Stdev = 1.2

4. How comfortable were you physically (your posture, legs, feet, etc.) when driving using the ACC system in comparison with your usual mode of driving?

1	2	3	4	5	6	7
Less Comfortable						More Comfortable

Mean = 5.1

Stdev = 1.2

5. How comfortable would you feel if your child, spouse, parents or other loved ones drove a vehicle equipped with ACC?

1	2	3	4	5	6	7
Very Uncomfortable						Very Comfortable

Mean = 6.0

Stdev = 1.0

6. How safe did you feel while driving in each of the following modes of operation?

	1	2	3	4	5	6	7
Manual Control	Very Unsafe						Very Safe

Mean = 6.3

Stdev = .8

	1	2	3	4	5	6	7
ACC	Very Unsafe						Very Safe

Mean = 6.0

Stdev = .8

7. How comfortable were you while driving in each of the following modes of operation?

	1	2	3	4	5	6	7
Manual Control	Very Uncomfortable						Very Comfortable

Mean = 5.9

Stdev = 1.2

ACC	1	2	3	4	5	6	7
	Very Uncomfortable						Very Comfortable

Mean = 6.3

Stdev = .6

8. How convenient did you find driving in each of the following modes of operation?

Manual Control	1	2	3	4	5	6	7
	Very Inconvenient						Very Convenient

Mean = 5.2

Stdev = 1.2

ACC	1	2	3	4	5	6	7
	Very Inconvenient						Very Convenient

Mean = 6.2

Stdev = .9

9. For each mode, rate the driving enjoyment that you experienced.

Manual Control	1	2	3	4	5	6	7
	Very Unenjoyable						Very Enjoyable

Mean = 5.0

Stdev = 1.3

ACC	1	2	3	4	5	6	7
	Very Unenjoyable						Very Enjoyable

Mean = 6.2

Stdev = .6

10. How fast did you drive when using the ACC system, as compared to driving manually?

1 2 3 4 5 6 7

Slower than manual — Faster than manual

Mean = 4.0

Stdev = 1.4

11. When using the ACC system, did you brake more or less than when you drive manually?

1 2 3 4 5 6 7

More braking than manual — Less braking than manual

Mean = 5.6

Stdev = 1.4

12. How cautious were you when you drove in each of the following modes?

Manual Control 1 2 3 4 5 6 7

Not cautious — Very Cautious

Mean = 5.4

Stdev = 1.2

ACC 1 2 3 4 5 6 7

Not cautious — Very Cautious

Mean = 5.4

Stdev = 1.1

13. What did you think of the rate of deceleration provided by the ACC system when following other vehicles?

1	2	3	4	5	6	7
Too Slow						Too Fast

Mean = 4.3

Stdev = 0.6

14. How safe did you feel when the ACC system decelerated in response to a slower moving vehicle?

1	2	3	4	5	6	7
Very Unsafe						Very Safe

Mean = 6.0

Stdev = 0.8

15. How safe did you feel when the ACC system decelerated in response to a cut-in?

1	2	3	4	5	6	7
Very Unsafe						Very Safe

Mean = 5.0

Stdev = 1.2

16. What did you think of the acceleration provided by the ACC system when pulling into an adjacent lane to pass other vehicles?

1	2	3	4	5	6	7
Too Slow						Too Fast

Mean = 4.0

Stdev = 1.4

17. How consistently did you maintain your speed when using the ACC system, as compared to driving manually?

1 2 3 4 5 6 7

Very Inconsistently — Very Consistently

Mean = 6.4

Stdev = 0.9

18. When using the ACC system, as compared to driving manually, did you find yourself more or less aware of the actions of vehicles around you?

1 2 3 4 5 6 7

Less Aware — More Aware

Mean = 4.8

Stdev = 1.4

19. When using the ACC system, as compared to driving manually, did you find yourself more or less responsive to the actions of vehicles around you?

1 2 3 4 5 6 7

Less Responsive — More Responsive

Mean = 4.6

Stdev = 1.3

20. When using the ACC system, did you ever feel you didn't understand what the system was doing, what was taking place, or how the ACC system might behave?

1 2 3 4 5 6 7

Very Frequently — Very Infrequently

Mean = 6.1

Stdev = 1.0

21. How easy or difficult did you find it to maintain a safe distance to the preceding vehicle using each of the following modes of operation?

Manual Control	1	2	3	4	5	6	7
	Very						Very
	Difficult						Easy

Mean = 4.8

Stdev = 1.6

ACC	1	2	3	4	5	6	7
	Very						Very
	Difficult						Easy

Mean = 6.3

Stdev = .7

22. How comfortable did you feel with your ability to change lanes (to pass other cars) using each of the following modes of operation?

Manual Control	1	2	3	4	5	6	7
	Very						Very
	Uncomfortable						Comfortable

Mean = 6.3

Stdev = .8

ACC	1	2	3	4	5	6	7
	Very						Very
	Uncomfortable						Comfortable

Mean = 5.8

Stdev = 1.4

23. How did using the ACC system affect your speed, relative to neighboring vehicles?

When using ACC on freeways and expressways, I drove:

1	2	3	4	5	6	7	0
Slower						Faster	Didn't Use

Mean = 4.6

Stdev = 1.3

24. How did using the ACC system affect your headway (following distance), as compared to manual control?

When using ACC on freeways and expressways, I drove:

1	2	3	4	5	6	7	0
Closer						Farther	Didn't Use

Mean = 5.1

Stdev = 1.4

25. How often, if ever, did you experience "unsafe" following distances when using the ACC system?

1	2	3	4	5	6	7
Very Frequently						Very Infrequently

Mean = 6.4

Stdev = 1.3

Briefly explain how this may have occurred:

26. Do you feel the headway adjustment feature useful?

1 2 3 4 5 6 7

Strongly Disagree — Strongly Agree

Mean = 6.3

Stdev = 1.0

Briefly explain your strategy for adjusting the headway (i.e., when you changed it, and why):

27. How safe did you feel using the ACC system?

1 2 3 4 5 6 7

Very Unsafe — Very Safe

Mean = 6.3

Stdev = 0.7

28. Do you think ACC is going to increase driving safety?

1 2 3 4 5 6 7

Strongly Disagree — Strongly Agree

Mean = 6.0

Stdev = .8

29. While driving using ACC, did you ever feel overly confident?

1 2 3 4 5 6 7

Strongly Disagree — Strongly Agree

Mean = 3.5

Stdev = 1.6

30. Did you feel more comfortable performing additional tasks, (e.g., adjusting the heater or the radio) while using the ACC system as compared to driving under manual control?

1 2 3 4 5 6 7

Strongly Disagree — Strongly Agree

Mean = 4.8

Stdev = 1.3

31. Did you find the ACC system functions distracting (e.g., automatic acceleration and deceleration)?

1 2 3 4 5 6 7

Very Distracting — Not At All Distracting

Mean = 6.1

Stdev = 1.1

32. Did you find the ACC system components distracting (e.g., status lights, control buttons)?

1 2 3 4 5 6 7

Very Distracting — Not At All Distracting

Mean = 5.7

Stdev = 1.5

33. While using the ACC system, how often, if ever, did the system fail to detect a preceding vehicle?

1 2 3 4 5 6 7

Always — Never

Mean = 6.6

Stdev = .5

34. While using the ACC system, how often, if ever, did the system produce false alarms (i.e., reported the presence of a vehicle when none existed)?

1 2 3 4 5 6 7

Always Never

Mean = 6.2

Stdev = 1.3

35. How easy or difficult do you feel it will be to market a vehicle equipped with an Adaptive Cruise Control (ACC) System?

1 2 3 4 5 6 7

Very Difficult Very Easy

Mean = 6.5

Stdev = .7

36. How comfortable would you feel if ACC systems replaced conventional cruise control?

1 2 3 4 5 6 7

Very Uncomfortable Very Comfortable

Mean = 6.5

Stdev = .8

37. Would you be willing buy an ACC system in your next new vehicle?

1 2 3 4 5 6 7

Very Unwilling Very Willing

Mean = 6.2

Stdev = 1.0

38. Approximately how much would you be willing to spend for this feature in a new vehicle?

$__________

39. Would you be willing to rent a vehicle equipped with an ACC system when you travel?

1	2	3	4	5	6	7
Very Unwilling						Very Willing

Mean = 6.6

Stdev =.6

40. Perhaps there were instances when the ACC system was decelerating and you had to intervene by applying the brakes. How easy was it to understand when to intervene?

41. In general, how does driving using the ACC system compare to driving with conventional cruise control?

42. Can you suggest any changes or modifications to the ACC system that might improve it?

43. Did you come close to having any accidents that you feel were related to using the ACC system?

APPENDIX E

BRAKE LATENCY TABLE

This appendix contains Table E-1 which is a a comprehensive set of data for 303 manual cases with hard braking as well as the 67 cases for ACC driving.

The table contains values of pertinent variables such as R, Rdot, V, Htm, and Tti as well as deceleration values (M2) for the preceding vehicle at the preceding vehicle intersection time (when the preceding vehicle started to brake at 0.1 g or greater). The table also contains values of the same variables as well as deceleration for the ACC-equipped vehicle at the ACC vehicle intersection time (when the ACC-equipped vehicle started to brake at 0.1 g or greater). For a complete description of the table see [12]

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	29	47	1	177	-15.7	93	77	1.90	11.3	0.15	0.13	92	-18.5	86	68	1.06	4.9	0.17	0.16	4.39	-2.49	18	5.1	1.26	1.14	1.29
Man	29	1	2	77	5.7	86	91	0.90	50.0	0.28	0.15	69	-4.4	83	78	0.83	15.7	0.22	0.21	2.80	-1.90	20	4.4	1.37	0.78	1.27
Man	89	114	3	44	3.2	84	87	0.53	50.0	0.17	0.15	40	-4.6	81	77	0.50	8.7	0.23	0.19	2.20	-1.67	10	1.7	1.27	1.32	1.23
Man	88	8	4	170	5.5	85	90	2.00	50.0	0.32	0.18	145	-15.9	85	69	1.70	9.1	0.37	0.31	3.63	-1.63	41	6.7	1.71	1.13	1.29
Man	96	19	5	139	1.4	103	105	1.34	50.0	0.15	0.14	120	-8.8	103	94	1.17	13.6	0.14	0.10	2.91	-1.57	10	2.7	0.73	0.89	1.16
Man	9	23	6	101	-1.5	79	78	1.28	50.0	0.21	0.16	72	-12.3	77	65	0.93	5.8	0.16	0.16	2.80	-1.52	10	2.5	0.99	0.75	1.24
Man	68	9	7	156	-5.7	98	93	1.59	27.6	0.27	0.16	112	-20.9	94	73	1.19	5.4	0.25	0.24	3.08	-1.49	18	4.0	1.53	0.95	1.18
Man	81	163	8	122	0.7	89	90	1.37	50.0	0.56	0.16	97	-18.0	86	69	1.12	5.4	0.56	0.56	2.85	-1.48	39	4.5	3.49	1.00	1.20
Man	88	1	9	110	2.2	89	92	1.23	50.0	0.14	0.11	101	-6.4	89	82	1.14	15.8	0.11	0.10	2.69	-1.46	6	1.8	0.93	0.78	1.13
Man	88	1	10	102	1.1	96	97	1.06	50.0	0.23	0.12	91	-8.4	93	85	0.98	10.9	0.20	0.17	2.52	-1.46	11	3.4	1.46	0.87	1.13
Man	89	142	11	203	-3.3	100	97	2.03	50.0	0.22	0.16	168	-15.7	95	80	1.77	10.7	0.29	0.23	3.46	-1.43	21	3.8	1.46	1.28	1.17
Man	4	69	12	127	-5.0	101	96	1.25	25.3	0.33	0.18	89	-15.9	97	81	0.92	5.6	0.36	0.35	2.63	-1.38	24	3.4	1.89	1.07	1.19
Man	66	334	13	140	-3.0	94	91	1.49	46.6	0.19	0.12	116	-11.5	90	79	1.28	10.1	0.21	0.18	2.86	-1.37	30	5.9	1.46	1.11	1.13
Man	31	33	14	84	-2.3	90	88	0.93	36.9	0.13	0.13	74	-5.0	86	81	0.86	14.7	0.16	0.15	2.20	-1.27	12	3.5	1.17	1.18	1.13
Man	73	181	15	35	0.9	75	76	0.47	50.0	0.24	0.16	27	-6.9	73	66	0.36	3.8	0.30	0.27	1.70	-1.23	16	3.0	1.65	1.24	1.21
Man	92	47	16	138	2.4	95	97	1.46	50.0	0.30	0.23	106	-18.9	95	76	1.12	5.6	0.14	0.12	2.69	-1.23	7	2.0	0.53	0.48	1.24
Man	52	48	17	62	-8.4	80	72	0.77	7.4	0.37	0.37	37	-13.3	78	64	0.48	2.8	0.23	0.22	1.82	-1.05	10	1.8	0.60	0.63	1.45
Man	52	52	18	170	-10.9	97	86	1.76	15.5	0.18	0.17	117	-20.8	95	74	1.24	5.7	0.19	0.16	2.80	-1.04	25	5.6	0.94	1.03	1.13
Man	68	9	19	82	-0.7	91	90	0.90	50.0	0.34	0.18	72	-7.7	88	80	0.82	9.4	0.38	0.34	1.93	-1.03	23	4.2	1.93	1.13	1.15
Man	68	125	20	107	4.0	92	96	1.17	50.0	0.28	0.19	97	-8.6	89	80	1.10	11.4	0.32	0.27	2.20	-1.03	20	3.9	1.44	1.16	1.16
Man	50	155	21	86	-10.2	96	86	0.90	8.5	0.22	0.17	59	-16.6	92	76	0.64	3.6	0.34	0.21	1.92	-1.02	32	4.4	1.25	1.52	1.13
Man	88	1	22	84	0.5	103	104	0.81	50.0	0.23	0.13	76	-5.7	103	97	0.74	13.3	0.21	0.20	1.71	-0.90	18	4.2	1.58	0.90	1.08
Man	19	17	23	143	-3.4	81	78	1.75	42.3	0.27	0.25	108	-18.4	78	60	1.38	5.9	0.28	0.27	2.64	-0.89	21	2.9	1.10	1.05	1.21
Man	59	78	24	123	-0.2	104	104	1.18	50.0	0.39	0.38	95	-18.3	102	84	0.94	5.2	0.30	0.23	2.04	-0.86	12	1.9	0.60	0.76	1.26
Man	61	52	25	104	1.5	84	86	1.23	50.0	0.33	0.13	97	-6.3	82	76	1.18	15.4	0.27	0.26	2.09	-0.86	17	2.8	2.01	0.82	1.09
Man	52	44	26	50	-2.6	100	97	0.50	19.0	0.14	0.12	43	-5.3	97	92	0.45	8.2	0.24	0.24	1.32	-0.82	10	1.4	1.92	1.68	1.07
Man	85	18	27	102	-1.1	75	74	1.35	50.0	0.30	0.21	81	-14.8	73	59	1.11	5.5	0.25	0.22	2.14	-0.79	36	7.8	1.03	0.82	1.17
Man	73	130	28	69	-3.4	98	94	0.70	20.3	0.17	0.13	60	-7.2	95	88	0.63	8.3	0.15	0.13	1.48	-0.78	7	1.6	0.98	0.88	1.07
Man	85	70	29	60	0.0	92	92	0.66	50.0	0.63	0.16	58	-2.2	91	89	0.64	26.7	0.32	0.29	1.43	-0.77	26	3.5	1.83	0.51	1.10
Man	96	90	30	63	-2.3	90	88	0.70	27.6	0.14	0.11	56	-5.7	89	83	0.64	9.8	0.19	0.19	1.43	-0.73	15	3.0	1.77	1.33	1.06
Man	56	71	31	107	-2.2	78	76	1.37	48.7	0.23	0.14	90	-8.6	75	67	1.19	10.5	0.18	0.17	2.09	-0.72	15	3.1	1.28	0.78	1.09
Man	85	217	32	48	-1.2	96	95	0.50	40.2	0.32	0.29	39	-8.9	94	85	0.42	4.4	0.35	0.33	1.21	-0.71	16	2.1	1.13	1.09	1.16
Man	81	176	33	81	-2.4	98	95	0.83	34.3	0.21	0.20	71	-7.6	94	86	0.76	9.4	0.37	0.31	1.54	-0.71	23	3.1	1.50	1.74	1.11
Man	87	174	34	71	-2.7	80	77	0.89	26.0	0.15	0.15	61	-7.7	77	69	0.79	7.9	0.16	0.16	1.59	-0.70	14	3.9	1.05	1.05	1.10

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	68	170	35	109	1.4	112	114	0.97	50.0	0.32	0.23	101	-7.9	110	102	0.92	12.7	0.23	0.18	1.65	-0.68	16	3.3	0.81	0.73	1.10
Man	96	76	36	206	-1.6	78	77	2.63	50.0	0.22	0.13	178	-13.8	75	61	2.38	12.9	0.21	0.19	3.30	-0.67	25	5.5	1.46	0.97	1.08
Man	85	41	37	86	-5.4	94	88	0.92	16.0	0.39	0.16	72	-10.4	91	80	0.79	6.9	0.28	0.17	1.59	-0.67	62	13.3	1.09	0.73	1.08
Man	64	4	38	67	-0.9	95	94	0.71	50.0	0.34	0.20	59	-7.7	94	86	0.63	7.8	0.38	0.14	1.37	-0.66	35	5.8	0.67	1.11	1.10
Man	85	76	39	86	-6.6	91	84	0.94	13.0	0.26	0.20	67	-13.4	89	75	0.76	5.0	0.40	0.39	1.60	-0.66	19	3.5	1.96	1.50	1.10
Man	63	189	40	196	-3.8	86	83	2.26	50.0	0.26	0.14	167	-13.4	84	71	1.98	12.5	0.23	0.18	2.91	-0.65	65	12.7	1.35	0.90	1.07
Man	63	278	41	79	2.3	79	81	1.00	50.0	0.21	0.19	73	-6.1	79	73	0.92	12.0	0.19	0.14	1.60	-0.60	7	1.7	0.71	0.92	1.10
Man	56	71	42	81	-2.8	92	89	0.89	28.8	0.27	0.21	67	-8.3	89	80	0.76	8.1	0.25	0.25	1.48	-0.59	21	4.2	1.22	0.94	1.09
Man	85	226	43	47	-2.0	87	85	0.54	23.6	0.18	0.11	44	-4.6	86	81	0.51	9.4	0.14	0.11	1.10	-0.56	6	1.5	1.03	0.77	1.05
Man	52	15	44	69	0.3	106	106	0.65	50.0	0.15	0.14	65	-3.7	104	100	0.62	17.4	0.26	0.21	1.21	-0.56	14	3.0	1.48	1.74	1.05
Man	85	272	45	122	2.3	106	108	1.16	50.0	0.24	0.24	114	-7.8	103	96	1.10	14.5	0.17	0.17	1.70	-0.54	13	3.9	0.73	0.72	1.08
Man	85	144	46	98	-5.6	104	99	0.95	17.7	0.24	0.18	84	-11.0	101	90	0.83	7.6	0.22	0.22	1.48	-0.53	14	3.0	1.23	0.94	1.06
Man	85	118	47	51	1.5	89	90	0.58	50.0	0.21	0.16	49	-3.0	87	84	0.56	16.1	0.21	0.20	1.10	-0.52	10	2.6	1.24	1.01	1.07
Man	52	53	48	48	-4.2	102	98	0.47	11.4	0.19	0.13	39	-8.5	103	94	0.38	4.6	0.37	0.30	0.99	-0.52	14	1.5	2.27	1.92	1.05
Man	52	56	49	48	-8.9	100	91	0.48	5.3	0.20	0.12	40	-10.4	99	89	0.41	3.9	0.20	0.16	0.99	-0.51	7	1.4	1.39	1.03	1.04
Man	88	207	50	85	1.2	77	78	1.10	50.0	0.24	0.19	78	-7.0	76	69	1.02	11.1	0.23	0.23	1.60	-0.50	12	3.6	1.20	0.95	1.09
Man	75	4	51	136	0.6	75	76	1.80	50.0	0.26	0.15	122	-10.8	75	65	1.61	11.2	0.26	0.19	2.30	-0.50	18	4.2	1.32	1.00	1.07
Man	77	72	52	82	-6.3	113	107	0.73	13.1	0.26	0.25	71	-11.6	111	100	0.64	6.1	0.20	0.18	1.21	-0.48	11	2.6	0.72	0.78	1.07
Man	81	92	53	72	1.1	85	86	0.84	50.0	0.24	0.15	67	-4.3	84	79	0.80	15.7	0.24	0.24	1.32	-0.48	17	3.8	1.59	1.02	1.06
Man	85	70	54	73	-3.1	86	83	0.85	23.6	0.25	0.15	64	-7.8	85	77	0.75	8.2	0.30	0.25	1.32	-0.47	24	4.3	1.63	1.18	1.06
Man	89	113	55	45	-0.5	77	76	0.58	50.0	0.20	0.15	42	-3.0	75	72	0.56	14.1	0.23	0.18	1.05	-0.47	25	6.7	1.20	1.15	1.06
Man	52	8	56	87	0.9	78	79	1.12	50.0	0.19	0.12	81	-5.2	76	71	1.07	15.7	0.24	0.24	1.59	-0.47	12	2.5	2.02	1.27	1.05
Man	88	1	57	90	-1.1	104	103	0.87	50.0	0.18	0.15	85	-5.4	103	98	0.82	15.8	0.23	0.21	1.32	-0.45	14	2.8	1.38	1.24	1.04
Man	44	91	58	405	-17.8	88	70	4.61	22.8	0.33	0.19	246	-40.9	84	43	2.92	6.0	0.26	0.26	5.06	-0.45	16	2.9	1.39	0.81	1.07
Man	52	47	59	68	1.0	95	96	0.71	50.0	0.17	0.13	64	-4.1	95	90	0.67	15.5	0.16	0.14	1.16	-0.45	10	2.2	1.03	0.92	1.04
Man	49	48	60	54	4.0	98	102	0.56	50.0	0.20	0.16	54	-1.2	98	96	0.55	45.4	0.22	0.18	0.99	-0.43	10	1.8	1.11	1.11	1.05
Man	85	37	61	84	-3.9	100	97	0.84	21.4	0.15	0.14	74	-8.9	100	91	0.74	8.3	0.17	0.15	1.26	-0.42	9	2.1	1.07	1.12	1.04
Man	96	2	62	94	-1.2	83	82	1.13	50.0	0.15	0.13	89	-4.1	80	76	1.11	21.6	0.14	0.12	1.54	-0.41	8	2.3	0.96	0.92	1.04
Man	76	25	63	29	-1.5	95	94	0.30	19.8	0.15	0.10	27	-2.4	95	92	0.29	11.5	0.13	0.13	0.71	-0.41	7	1.7	1.26	0.87	1.03
Man	61	52	64	147	-1.7	77	75	1.91	50.0	0.25	0.24	123	-15.0	75	60	1.63	8.2	0.23	0.21	2.31	-0.40	18	2.8	0.87	0.89	1.09
Man	85	130	65	45	-0.2	76	76	0.59	50.0	0.22	0.17	41	-4.3	75	70	0.55	9.7	0.18	0.12	0.99	-0.40	7	2.0	0.67	0.79	1.06
Man	3	28	66	173	-1.3	78	77	2.20	50.0	0.30	0.18	130	-18.5	77	58	1.69	7.0	0.25	0.24	2.59	-0.39	31	7.0	1.35	0.81	1.06
Man	29	22	67	171	-1.9	107	105	1.59	50.0	0.22	0.14	156	-7.3	104	97	1.49	21.3	0.18	0.17	1.98	-0.39	10	2.6	1.29	0.80	1.03
Man	73	83	68	34	0.0	75	75	0.46	50.0	0.18	0.16	32	-2.7	73	71	0.44	11.8	0.20	0.19	0.83	-0.37	10	2.1	1.12	1.11	1.06
Man	73	121	69	32	0.6	79	80	0.40	50.0	0.27	0.15	31	-1.2	78	77	0.40	26.0	0.20	0.18	0.77	-0.37	22	4.8	1.23	0.73	1.05

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	80	3	70	39	-1.6	77	75	0.51	23.8	0.20	0.16	36	-4.5	75	71	0.47	8.0	0.20	0.20	0.87	-0.36	26	7.1	1.29	0.99	1.05
Man	90	142	71	81	-4.6	76	72	1.07	17.9	0.18	0.17	71	-8.7	73	65	0.96	8.1	0.24	0.21	1.43	-0.36	23	5.6	1.21	1.32	1.06
Man	76	120	72	82	-4.0	98	94	0.84	20.5	0.22	0.16	71	-10.0	97	87	0.73	7.1	0.23	0.20	1.20	-0.36	15	3.1	1.21	1.06	1.04
Man	68	126	73	118	-2.3	88	86	1.35	50.0	0.24	0.21	104	-10.1	86	76	1.21	10.3	0.29	0.25	1.70	-0.35	25	5.8	1.17	1.22	1.06
Man	68	125	74	77	-1.4	90	89	0.86	50.0	0.17	0.17	73	-4.5	88	83	0.83	16.3	0.18	0.18	1.20	-0.34	12	3.5	1.07	1.10	1.04
Man	7	6	75	53	0.7	81	82	0.65	50.0	0.31	0.17	48	-2.7	80	77	0.60	17.6	0.25	0.13	0.99	-0.34	41	8.7	0.72	0.81	1.05
Man	77	145	76	99	-1.0	115	114	0.86	50.0	0.16	0.14	96	-3.0	112	109	0.86	32.0	0.26	0.26	1.20	-0.34	18	3.5	1.78	1.60	1.03
Man	89	259	77	130	-3.6	86	83	1.50	36.5	0.29	0.22	113	-12.9	83	70	1.37	8.7	0.16	0.15	1.81	-0.31	19	5.0	0.68	0.55	1.05
Man	68	147	78	63	-1.3	102	101	0.62	49.6	0.18	0.15	60	-4.0	101	97	0.59	15.0	0.20	0.18	0.93	-0.31	10	2.4	1.17	1.12	1.03
Man	61	52	79	89	-3.2	75	72	1.18	28.0	0.25	0.22	77	-10.5	73	63	1.06	7.4	0.27	0.22	1.49	-0.31	21	5.1	1.01	1.07	1.06
Man	89	271	80	33	0.5	82	83	0.41	50.0	0.15	0.14	32	-1.6	81	80	0.40	19.6	0.15	0.12	0.71	-0.30	10	3.0	0.85	1.00	1.03
Man	68	62	81	106	-1.8	81	80	1.30	50.0	0.16	0.13	98	-6.5	80	73	1.22	15.1	0.18	0.13	1.60	-0.30	8	2.2	0.99	1.09	1.03
Man	61	25	82	63	-4.4	78	73	0.81	14.4	0.24	0.20	55	-8.1	76	68	0.72	6.8	0.20	0.20	1.10	-0.29	9	1.8	0.98	0.84	1.05
Man	66	210	83	235	-2.6	78	75	3.02	50.0	0.29	0.22	184	-18.9	75	57	2.44	9.8	0.17	0.15	3.30	-0.28	8	2.0	0.66	0.60	1.06
Man	68	74	84	80	3.2	86	89	0.94	50.0	0.34	0.30	73	-8.3	85	77	0.86	8.8	0.33	0.29	1.21	-0.27	34	5.6	0.95	0.98	1.07
Man	34	82	85	90	2.0	101	103	0.89	50.0	0.40	0.32	83	-7.7	99	91	0.84	10.9	0.36	0.30	1.15	-0.26	22	2.9	0.93	0.90	1.06
Man	10	36	86	79	2.0	75	77	1.06	50.0	0.23	0.15	74	-2.5	73	71	1.02	30.3	0.18	0.15	1.32	-0.26	11	2.3	1.01	0.76	1.03
Man	29	47	87	33	-1.0	91	90	0.36	33.1	0.15	0.10	32	-1.4	90	89	0.35	23.3	0.17	0.14	0.61	-0.25	7	1.4	1.37	1.13	1.02
Man	1	98	88	86	0.5	79	80	1.08	50.0	0.29	0.21	78	-4.2	77	73	1.02	18.6	0.20	0.20	1.32	-0.24	14	3.6	0.98	0.69	1.04
Man	85	174	89	82	-3.3	84	81	0.97	25.0	0.31	0.15	75	-7.1	83	76	0.91	10.6	0.27	0.15	1.21	-0.24	72	15.0	1.00	0.84	1.03
Man	87	177	90	15	-1.3	100	99	0.15	12.1	0.14	0.11	14	-2.2	100	98	0.14	6.4	0.13	0.10	0.39	-0.24	7	1.9	0.92	0.95	1.02
Man	73	110	91	77	-1.7	89	88	0.87	44.7	0.30	0.29	70	-8.5	89	80	0.78	8.2	0.26	0.22	1.10	-0.23	15	3.2	0.76	0.86	1.05
Man	85	223	92	97	-10.7	100	90	0.97	9.1	0.29	0.28	77	-18.2	98	80	0.79	4.2	0.42	0.18	1.20	-0.23	26	3.9	0.63	1.43	1.04
Man	14	16	93	64	-5.7	84	79	0.76	11.2	0.26	0.20	53	-11.4	83	71	0.65	4.7	0.26	0.24	0.99	-0.23	15	2.7	1.20	1.00	1.04
Man	89	51	94	109	1.4	74	75	1.48	50.0	0.29	0.25	94	-12.4	74	62	1.27	7.6	0.29	0.22	1.70	-0.22	65	11.4	0.89	0.99	1.05
Man	69	1	95	69	0.0	78	78	0.88	50.0	0.30	0.19	66	-3.5	76	73	0.87	19.1	0.23	0.18	1.10	-0.22	20	5.1	0.99	0.76	1.04
Man	77	18	96	109	-4.6	86	81	1.27	23.4	0.20	0.17	96	-10.8	84	73	1.14	8.8	0.18	0.13	1.48	-0.21	10	2.7	0.74	0.92	1.03
Man	85	35	97	53	3.3	104	107	0.51	50.0	0.44	0.43	50	-4.5	103	99	0.49	11.2	0.32	0.27	0.72	-0.21	13	1.9	0.62	0.72	1.06
Man	44	65	98	83	6.5	74	80	1.12	50.0	0.34	0.22	82	-2.6	75	72	1.10	31.2	0.29	0.22	1.32	-0.20	40	5.8	0.99	0.83	1.04
Man	85	77	99	48	0.5	84	84	0.57	50.0	0.31	0.22	45	-3.8	83	79	0.54	11.7	0.34	0.32	0.77	-0.20	15	2.3	1.42	1.10	1.04
Man	85	35	100	43	-2.5	102	99	0.43	17.6	0.22	0.22	40	-4.7	100	96	0.40	8.5	0.23	0.22	0.61	-0.18	15	3.3	0.97	1.01	1.03
Man	52	47	101	71	-0.2	77	77	0.92	50.0	0.16	0.12	69	-2.3	75	73	0.91	30.2	0.18	0.17	1.10	-0.18	10	2.9	1.50	1.10	1.02
Man	50	73	102	97	-2.2	81	79	1.19	44.4	0.25	0.17	89	-7.3	80	73	1.11	12.2	0.26	0.19	1.37	-0.18	33	6.0	1.11	1.05	1.02
Man	8	79	103	93	-8.3	89	81	1.04	11.2	0.25	0.13	81	-9.8	86	77	0.93	8.2	0.33	0.31	1.21	-0.17	25	4.6	2.47	1.32	1.02
Man	6	10	104	172	-0.5	76	76	2.26	50.0	0.24	0.18	146	-11.6	74	62	1.97	12.6	0.13	0.12	2.41	-0.15	10	2.8	0.66	0.55	1.02

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	34	82	105	60	0.5	98	98	0.62	50.0	0.35	0.32	56	-5.1	96	91	0.59	11.1	0.40	0.32	0.77	-0.15	22	2.9	1.00	1.12	1.03
Man	4	69	106	67	-0.3	85	85	0.79	50.0	0.25	0.18	62	-3.6	85	81	0.73	16.9	0.23	0.17	0.93	-0.14	11	2.1	0.91	0.94	1.02
Man	96	100	107	90	-2.1	89	87	1.01	42.9	0.41	0.10	85	-4.1	87	83	0.98	20.8	0.29	0.17	1.15	-0.14	29	5.4	1.70	0.70	1.01
Man	87	69	108	73	-0.4	76	76	0.96	50.0	0.35	0.20	68	-5.3	75	69	0.91	12.8	0.35	0.33	1.10	-0.14	22	3.3	1.61	1.00	1.02
Man	78	195	109	98	-3.5	91	87	1.08	28.2	0.32	0.32	86	-11.7	88	76	0.98	7.4	0.31	0.29	1.21	-0.13	25	3.9	0.90	0.97	1.03
Man	30	15	110	127	-5.7	86	81	1.47	22.2	0.17	0.12	114	-10.0	85	75	1.34	11.3	0.22	0.15	1.59	-0.12	11	2.7	1.23	1.24	1.01
Man	68	125	111	58	-4.3	97	93	0.60	13.6	0.37	0.28	53	-7.4	95	88	0.56	7.2	0.46	0.27	0.71	-0.11	35	4.2	0.95	1.23	1.02
Man	85	39	112	61	-9.1	74	65	0.82	6.7	0.26	0.23	50	-12.9	73	60	0.68	3.8	0.30	0.28	0.93	-0.11	14	2.7	1.19	1.18	1.02
Man	41	47	113	15	-1.6	87	86	0.17	9.2	0.23	0.17	15	-1.6	86	84	0.17	9.0	0.27	0.25	0.28	-0.11	12	2.6	1.46	1.16	1.01
Man	4	44	114	39	-2.7	99	96	0.39	14.2	0.23	0.23	36	-3.9	98	94	0.37	9.1	0.21	0.19	0.49	-0.10	10	2.1	0.84	0.92	1.01
Man	89	158	115	101	-6.3	101	95	1.00	16.1	0.21	0.13	89	-12.0	100	88	0.89	7.4	0.20	0.16	1.10	-0.10	13	3.1	1.24	0.97	1.01
Man	66	157	116	102	-8.7	95	87	1.07	11.8	0.42	0.35	81	-20.1	93	73	0.87	4.0	0.54	0.48	1.16	-0.09	34	3.4	1.38	1.28	1.02
Man	87	108	117	99	-3.3	88	85	1.13	30.2	0.40	0.22	93	-7.0	86	79	1.08	13.2	0.24	0.22	1.21	-0.08	20	4.6	1.01	0.61	1.01
Man	49	3	118	85	-1.7	100	98	0.85	49.1	0.26	0.16	81	-5.0	100	95	0.82	16.2	0.19	0.14	0.93	-0.08	7	1.7	0.88	0.73	1.01
Man	55	66	119	78	2.3	90	92	0.87	50.0	0.21	0.19	76	-3.3	90	87	0.84	23.1	0.14	0.14	0.94	-0.07	7	2.1	0.72	0.64	1.01
Man	85	34	120	68	-7.5	98	90	0.70	9.1	0.20	0.16	60	-10.6	96	85	0.62	5.6	0.26	0.24	0.77	-0.07	24	4.7	1.49	1.30	1.01
Man	52	47	121	64	-1.3	89	88	0.71	49.9	0.45	0.32	59	-6.6	88	81	0.67	8.9	0.40	0.33	0.77	-0.06	19	2.4	1.05	0.90	1.01
Man	85	1	122	32	-1.0	74	73	0.43	32.1	0.19	0.15	30	-4.0	74	70	0.40	7.4	0.18	0.13	0.49	-0.06	7	1.7	0.86	0.95	1.01
Man	9	63	123	216	-1.5	84	83	2.56	50.0	0.26	0.10	192	-10.0	84	74	2.30	19.2	0.20	0.15	2.59	-0.03	10	2.5	1.47	0.76	1.00
Man	85	18	124	41	2.4	97	99	0.42	50.0	0.24	0.20	40	0.0	96	96	0.42	50.0	0.20	0.15	0.44	-0.02	9	1.9	0.75	0.82	1.00
Man	88	176	125	145	-1.1	81	80	1.80	50.0	0.31	0.17	133	-10.2	81	71	1.63	13.0	0.27	0.26	1.81	-0.01	42	6.4	1.52	0.89	1.00
Man	1	37	126	92	-1.1	88	87	1.04	50.0	0.23	0.19	86	-4.0	87	83	0.99	21.5	0.19	0.19	1.05	-0.01	16	3.9	0.99	0.84	1.00
Man	85	144	127	54	-0.4	108	107	0.50	50.0	0.17	0.12	54	-0.5	108	107	0.50	50.0	0.21	0.12	0.50	0.00	9	2.5	1.02	1.24	1.00
Man	93	89	128	153	-6.5	77	70	1.99	23.6	0.38	0.14	126	-16.0	75	59	1.67	7.9	0.46	0.20	1.98	0.01	43	5.2	1.38	1.21	1.00
Man	68	53	129	53	0.5	74	74	0.72	50.0	0.25	0.23	51	-3.0	73	70	0.69	16.9	0.17	0.16	0.71	0.01	11	2.9	0.70	0.67	1.00
Man	80	3	130	85	-2.3	103	100	0.83	37.4	0.27	0.23	80	-6.5	102	95	0.79	12.4	0.26	0.15	0.82	0.01	48	10.4	0.66	0.96	1.00
Man	85	70	131	54	-1.8	86	85	0.62	29.5	0.21	0.14	51	-4.8	86	82	0.59	10.5	0.26	0.18	0.60	0.02	12	3.0	1.26	1.23	1.00
Man	63	290	132	92	-10.8	82	71	1.12	8.6	0.23	0.22	76	-15.9	81	65	0.93	4.8	0.19	0.16	1.10	0.02	24	5.6	0.72	0.84	1.00
Man	87	140	133	45	-4.6	98	93	0.46	9.7	0.16	0.11	44	-4.5	97	92	0.45	9.8	0.15	0.13	0.44	0.02	9	2.3	1.22	0.89	1.00
Man	85	37	134	245	-11.8	96	84	2.55	20.8	0.32	0.19	197	-24.5	92	67	2.15	8.0	0.40	0.36	2.52	0.03	52	6.6	1.86	1.24	1.00
Man	85	307	135	43	-0.5	81	80	0.53	50.0	0.23	0.19	41	-2.9	81	78	0.51	14.1	0.20	0.15	0.50	0.03	8	1.5	0.81	0.86	1.00
Man	52	53	136	78	-3.0	95	92	0.83	26.0	0.16	0.10	74	-4.5	95	90	0.79	16.7	0.19	0.10	0.77	0.06	6	1.3	0.98	1.23	1.00
Man	73	18	137	149	-7.2	77	70	1.93	20.6	0.23	0.17	123	-16.0	74	58	1.66	7.7	0.26	0.22	1.87	0.06	9	1.5	1.27	1.13	0.99
Man	56	113	138	27	-7.4	94	86	0.28	3.6	0.14	0.10	26	-7.4	94	86	0.28	3.6	0.15	0.14	0.22	0.06	10	2.8	1.38	1.12	1.00
Man	88	177	139	68	-2.1	100	98	0.68	32.4	0.58	0.44	63	-7.6	100	92	0.63	8.3	0.53	0.49	0.60	0.08	29	2.3	1.12	0.91	0.98

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	84	27	140	89	-3.2	75	72	1.18	27.9	0.24	0.12	84	-4.6	75	70	1.13	18.5	0.18	0.15	1.10	0.08	11	3.0	1.25	0.76	0.99
Man	49	16	141	61	-2.4	90	88	0.68	25.9	0.14	0.14	59	-3.4	89	86	0.66	17.6	0.20	0.17	0.60	0.08	9	2.9	1.22	1.45	0.99
Man	61	42	142	138	2.7	78	80	1.78	50.0	0.24	0.15	136	-2.7	75	73	1.80	49.8	0.20	0.17	1.70	0.08	76	21.7	1.17	0.81	0.99
Man	55	79	143	84	-3.1	78	75	1.07	27.2	0.21	0.18	77	-7.3	77	70	1.01	10.6	0.21	0.19	0.99	0.08	10	2.0	1.10	1.01	0.99
Man	63	78	144	98	-2.2	78	76	1.25	44.7	0.19	0.12	94	-3.9	76	72	1.23	23.9	0.17	0.16	1.15	0.10	21	6.3	1.37	0.90	0.99
Man	12	36	145	38	-0.4	80	80	0.48	50.0	0.15	0.12	38	-0.6	79	79	0.48	50.0	0.15	0.13	0.38	0.10	8	2.2	1.07	0.99	0.99
Man	85	35	146	81	-3.9	99	95	0.82	20.7	0.21	0.17	75	-7.9	98	90	0.77	9.5	0.15	0.11	0.72	0.10	10	2.9	0.66	0.72	0.99
Man	1	47	147	240	-1.0	89	88	2.68	50.0	0.25	0.18	206	-13.7	89	75	2.32	15.1	0.22	0.20	2.58	0.10	21	4.2	1.10	0.87	0.99
Man	96	2	148	73	-1.8	74	72	0.98	40.0	0.30	0.24	69	-5.8	74	68	0.93	11.8	0.26	0.26	0.88	0.10	13	2.4	1.09	0.89	0.98
Man	12	1	149	83	-3.6	80	76	1.03	23.3	0.14	0.14	77	-5.6	79	74	0.97	13.9	0.16	0.16	0.93	0.10	12	2.6	1.10	1.15	0.99
Man	14	17	150	25	-0.6	75	75	0.33	39.6	0.26	0.24	25	-1.1	75	74	0.33	22.8	0.19	0.14	0.22	0.11	7	1.3	0.57	0.73	0.98
Man	73	181	151	32	-0.3	95	95	0.34	50.0	0.18	0.15	32	-0.5	95	94	0.34	50.0	0.14	0.13	0.22	0.12	10	3.0	0.88	0.79	0.99
Man	4	44	152	26	-3.3	90	87	0.29	8.0	0.42	0.25	25	-3.6	89	85	0.28	7.1	0.40	0.36	0.16	0.13	20	2.6	1.44	0.96	0.98
Man	88	161	153	51	-3.2	95	92	0.53	15.8	0.36	0.27	48	-4.6	94	89	0.51	10.4	0.45	0.24	0.39	0.14	27	3.6	0.91	1.27	0.98
Man	73	181	154	37	-1.6	78	77	0.47	22.6	0.17	0.11	37	-1.4	78	76	0.47	26.9	0.15	0.13	0.33	0.14	15	4.4	1.14	0.87	0.99
Man	21	1	155	75	1.5	82	84	0.92	50.0	0.38	0.26	73	-2.7	82	79	0.89	26.9	0.24	0.20	0.77	0.15	19	3.6	0.75	0.62	0.97
Man	85	136	156	56	-3.6	87	84	0.64	15.3	0.33	0.33	53	-4.6	86	81	0.62	11.4	0.31	0.27	0.49	0.15	14	2.5	0.84	0.96	0.97
Man	59	66	157	33	-3.0	76	73	0.43	10.9	0.53	0.53	31	-5.8	75	69	0.41	5.2	0.49	0.45	0.28	0.15	38	3.9	0.86	0.93	0.94
Man	30	20	158	115	-2.1	84	81	1.38	50.0	0.20	0.13	109	-6.5	84	77	1.30	16.8	0.16	0.14	1.21	0.17	10	2.6	1.07	0.82	0.98
Man	89	212	159	147	-7.0	107	100	1.37	20.9	0.17	0.13	135	-10.2	106	95	1.28	13.2	0.48	0.37	1.20	0.17	23	2.3	2.91	2.77	0.99
Man	52	55	160	51	-4.5	77	72	0.66	11.4	0.29	0.29	47	-6.7	75	69	0.63	7.0	0.29	0.28	0.49	0.17	23	3.7	0.97	1.01	0.96
Man	59	67	161	86	-2.5	81	79	1.05	34.8	0.32	0.24	81	-7.0	80	73	1.01	11.6	0.17	0.16	0.88	0.17	35	8.9	0.66	0.52	0.97
Man	49	48	162	92	-2.7	91	88	1.01	33.6	0.16	0.13	88	-5.3	91	86	0.97	16.6	0.19	0.13	0.82	0.19	23	5.4	1.00	1.23	0.98
Man	61	2	163	91	-7.1	77	70	1.18	12.8	0.30	0.26	81	-10.9	75	64	1.08	7.4	0.20	0.17	0.99	0.19	14	2.6	0.68	0.69	0.96
Man	4	90	164	46	0.1	80	80	0.57	50.0	0.42	0.39	43	-1.7	79	77	0.54	24.8	0.28	0.27	0.38	0.19	16	2.6	0.69	0.68	0.94
Man	50	13	165	85	-6.6	75	68	1.14	12.9	0.32	0.30	75	-11.3	74	63	1.02	6.7	0.22	0.21	0.94	0.20	26	6.0	0.70	0.70	0.95
Man	4	103	166	113	-7.1	96	89	1.18	15.9	0.38	0.16	102	-9.5	95	85	1.08	10.8	0.33	0.17	0.98	0.20	48	8.7	1.05	0.88	0.98
Man	88	1	167	107	-1.3	111	109	0.97	50.0	0.32	0.32	103	-6.0	110	104	0.94	17.1	0.25	0.23	0.77	0.20	24	4.3	0.73	0.77	0.96
Man	56	91	168	102	-3.1	86	83	1.18	32.9	0.20	0.20	93	-7.0	84	77	1.11	13.3	0.15	0.15	0.98	0.20	10	3.1	0.78	0.77	0.97
Man	68	125	169	117	-3.6	109	105	1.08	33.0	0.24	0.23	111	-7.8	107	99	1.03	14.1	0.21	0.20	0.87	0.21	32	7.0	0.87	0.91	0.97
Man	88	1	170	109	-5.0	87	82	1.25	21.8	0.75	0.42	95	-15.1	84	69	1.13	6.3	0.44	0.43	1.04	0.21	48	6.0	1.02	0.58	0.94
Man	1	111	171	44	-1.1	80	79	0.55	39.9	0.20	0.17	43	-1.5	80	78	0.54	29.7	0.20	0.16	0.33	0.22	27	5.4	0.93	1.01	0.97
Man	85	1	172	46	-1.2	83	82	0.55	38.8	0.27	0.27	45	-2.5	83	80	0.54	18.3	0.24	0.16	0.33	0.22	18	3.4	0.61	0.89	0.96
Man	59	58	173	73	-2.1	100	98	0.74	35.1	0.46	0.44	70	-7.3	99	92	0.70	9.5	0.56	0.32	0.50	0.24	35	3.5	0.72	1.21	0.94
Man	85	239	174	145	-3.6	102	98	1.42	40.7	0.35	0.32	130	-14.9	103	88	1.27	8.7	0.25	0.23	1.16	0.26	21	3.7	0.71	0.73	0.95

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	85	37	175	60	-1.1	90	89	0.67	50.0	0.23	0.20	59	-2.7	90	87	0.65	21.5	0.18	0.13	0.39	0.28	8	2.2	0.67	0.76	0.96
Man	52	63	176	80	-6.1	91	85	0.88	13.1	0.22	0.19	75	-6.8	90	83	0.84	11.0	0.32	0.29	0.60	0.28	12	1.7	1.54	1.48	0.96
Man	40	58	177	65	-1.3	84	82	0.77	50.0	0.15	0.13	63	-2.2	83	81	0.76	28.9	0.14	0.13	0.49	0.28	10	2.5	1.03	0.95	0.97
Man	88	207	178	60	0.5	108	108	0.56	50.0	0.21	0.14	60	-0.5	108	107	0.55	50.0	0.19	0.14	0.27	0.29	8	1.7	0.98	0.91	0.98
Man	59	4	179	102	-4.2	101	97	1.01	24.3	0.32	0.30	95	-9.0	100	91	0.95	10.6	0.20	0.15	0.71	0.30	6	1.2	0.49	0.62	0.95
Man	89	131	180	117	-2.6	87	85	1.35	46.0	0.24	0.19	112	-5.8	86	80	1.31	19.2	0.22	0.22	1.05	0.30	18	3.6	1.15	0.93	0.96
Man	85	136	181	44	-3.1	84	80	0.52	14.1	0.16	0.16	43	-3.6	83	79	0.51	12.0	0.28	0.25	0.22	0.30	12	2.1	1.60	1.76	0.96
Man	75	48	182	83	-4.3	81	77	1.02	19.4	0.20	0.17	78	-7.0	81	74	0.96	11.2	0.15	0.13	0.71	0.31	9	2.5	0.77	0.75	0.96
Man	59	68	183	58	-0.6	97	96	0.60	50.0	0.47	0.44	57	-3.6	97	93	0.59	16.0	0.39	0.25	0.28	0.32	12	1.8	0.58	0.83	0.91
Man	4	69	184	75	-1.2	98	97	0.76	50.0	0.21	0.19	73	-2.0	97	95	0.76	36.7	0.21	0.21	0.44	0.32	15	3.1	1.11	1.00	0.96
Man	4	44	185	42	-1.7	95	94	0.44	24.3	0.22	0.22	42	-2.0	95	93	0.44	20.8	0.20	0.19	0.11	0.33	10	1.9	0.89	0.94	0.95
Man	77	213	186	53	3.4	79	83	0.67	50.0	0.31	0.29	53	1.5	79	81	0.67	50.0	0.23	0.13	0.33	0.34	7	1.1	0.44	0.76	0.93
Man	83	1	187	56	-3.6	82	79	0.68	15.7	0.34	0.29	54	-3.8	81	78	0.67	14.2	0.29	0.25	0.33	0.35	15	2.3	0.87	0.83	0.93
Man	85	224	188	158	-10.5	77	66	2.06	15.1	0.28	0.15	135	-15.6	75	60	1.79	8.7	0.23	0.22	1.71	0.35	15	4.1	1.46	0.82	0.96
Man	1	46	189	58	-3.0	92	89	0.63	19.4	0.18	0.18	57	-3.7	92	88	0.62	15.2	0.17	0.16	0.28	0.35	12	2.7	0.88	0.96	0.96
Man	4	49	190	62	-2.3	98	96	0.63	27.4	0.80	0.73	58	-4.8	97	92	0.60	12.0	0.63	0.61	0.28	0.35	57	4.9	0.83	0.78	0.85
Man	1	111	191	76	1.3	79	80	0.96	50.0	0.32	0.32	72	-1.8	78	77	0.92	39.4	0.21	0.20	0.60	0.36	12	2.5	0.64	0.65	0.92
Man	56	109	192	58	-3.0	73	70	0.80	19.4	0.18	0.15	56	-3.8	73	69	0.77	14.7	0.17	0.12	0.44	0.36	34	9.7	0.77	0.94	0.95
Man	49	18	193	66	-1.1	89	88	0.74	50.0	0.48	0.45	63	-3.4	88	85	0.72	18.8	0.42	0.41	0.38	0.36	54	10.1	0.91	0.88	0.89
Man	59	78	194	143	-0.5	102	101	1.40	50.0	0.69	0.42	132	-14.0	100	86	1.33	9.4	0.23	0.22	1.04	0.36	33	7.2	0.53	0.34	0.91
Man	68	170	195	145	-4.6	99	94	1.47	31.2	0.20	0.18	137	-7.9	96	88	1.43	17.3	0.17	0.17	1.10	0.37	10	2.5	0.96	0.87	0.96
Man	89	263	196	84	-0.9	84	83	1.00	50.0	0.26	0.23	82	-2.6	84	81	0.99	31.2	0.22	0.21	0.61	0.39	37	11.0	0.92	0.85	0.94
Man	89	142	197	176	-3.3	97	94	1.82	50.0	0.26	0.20	166	-9.3	95	85	1.75	17.8	0.21	0.17	1.43	0.39	17	3.2	0.88	0.82	0.95
Man	20	41	198	63	-2.4	82	80	0.77	26.7	0.36	0.28	61	-3.6	81	78	0.75	17.1	0.35	0.20	0.38	0.39	29	3.9	0.70	0.97	0.92
Man	34	81	199	57	-2.2	84	81	0.68	25.9	0.32	0.25	55	-3.5	84	80	0.66	16.0	0.25	0.20	0.28	0.40	13	3.0	0.80	0.78	0.93
Man	78	181	200	115	-0.9	84	83	1.38	50.0	0.27	0.26	111	-5.4	82	77	1.35	20.7	0.15	0.15	0.98	0.40	15	3.8	0.57	0.57	0.92
Man	57	47	201	167	1.0	79	80	2.11	50.0	0.28	0.17	160	-6.3	76	70	2.11	25.5	0.22	0.16	1.70	0.41	54	11.8	0.94	0.79	0.94
Man	77	253	202	77	-2.9	97	94	0.79	26.3	0.11	0.10	75	-3.5	97	93	0.78	21.8	0.18	0.11	0.38	0.41	7	1.7	1.11	1.60	0.97
Man	4	61	203	87	-6.0	94	88	0.92	14.4	0.17	0.11	83	-6.4	93	87	0.89	13.1	0.17	0.15	0.50	0.42	8	1.8	1.29	0.99	0.97
Man	4	105	204	92	-6.7	89	83	1.03	13.8	0.19	0.18	88	-7.2	88	81	1.00	12.2	0.30	0.29	0.60	0.43	20	3.5	1.63	1.52	0.95
Man	44	85	205	98	-2.8	75	72	1.31	34.6	0.41	0.39	88	-12.1	73	61	1.20	7.2	0.36	0.30	0.88	0.43	28	3.4	0.76	0.89	0.87
Man	89	142	206	89	-1.2	109	107	0.82	50.0	0.17	0.16	88	-1.9	108	106	0.82	46.1	0.26	0.25	0.39	0.43	14	2.3	1.60	1.51	0.96
Man	89	263	207	217	0.5	84	85	2.57	50.0	0.39	0.31	195	-16.7	82	65	2.37	11.7	0.30	0.28	2.14	0.43	19	3.5	0.89	0.79	0.91
Man	63	290	208	115	-2.0	81	79	1.42	50.0	0.34	0.20	110	-5.7	79	74	1.38	19.4	0.26	0.18	0.99	0.43	80	15.6	0.91	0.76	0.93
Man	8	29	209	113	-10.6	108	97	1.05	10.7	0.19	0.10	107	-10.8	108	97	0.99	9.9	0.22	0.16	0.61	0.44	7	1.2	1.51	1.17	0.97

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng ft	Rdot, ft/s	V_1 ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT,s	Htm-WT,s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	14	17	210	94	-1.3	86	84	1.10	50.0	0.52	0.45	88	-8.8	84	75	1.05	10.0	0.36	0.31	0.66	0.44	75	14.8	0.69	0.69	0.87
Man	7	15	211	125	-2.8	78	76	1.59	44.2	0.41	0.28	111	-9.2	76	67	1.45	12.0	0.42	0.20	1.15	0.44	71	8.8	0.73	1.02	0.91
Man	81	36	212	76	-2.0	73	71	1.04	38.1	0.29	0.26	73	-5.6	73	68	0.99	13.1	0.27	0.26	0.60	0.44	25	6.6	0.99	0.91	0.91
Man	4	69	213	72	-3.6	87	84	0.82	20.2	0.20	0.17	69	-4.4	86	82	0.80	15.8	0.17	0.13	0.38	0.44	8	1.9	0.77	0.88	0.95
Man	68	125	214	96	-1.5	100	99	0.95	50.0	0.19	0.19	94	-3.6	100	96	0.94	26.4	0.18	0.17	0.50	0.45	14	3.6	0.92	0.91	0.95
Man	52	17	215	49	-4.5	85	81	0.57	10.9	0.30	0.30	48	-4.3	85	81	0.57	11.3	0.35	0.33	0.11	0.46	22	3.6	1.08	1.16	0.90
Man	4	49	216	58	-1.5	85	84	0.68	39.8	0.26	0.23	57	-2.1	85	83	0.67	27.2	0.23	0.19	0.22	0.46	15	3.5	0.81	0.89	0.93
Man	63	290	217	152	0.0	83	83	1.84	50.0	0.32	0.23	143	-8.4	81	73	1.76	17.1	0.31	0.14	1.37	0.47	82	16.4	0.60	0.97	0.92
Man	77	1	218	108	-8.8	101	92	1.07	12.2	0.32	0.31	102	-10.8	100	89	1.02	9.4	0.42	0.21	0.60	0.47	35	4.4	0.69	1.32	0.92
Man	7	12	219	59	-2.0	85	83	0.69	29.3	0.28	0.25	57	-2.7	84	82	0.68	20.9	0.18	0.16	0.22	0.47	12	2.8	0.63	0.65	0.92
Man	81	36	220	84	0.5	78	78	1.08	50.0	0.22	0.19	81	-4.3	78	73	1.04	18.9	0.20	0.13	0.60	0.48	9	1.7	0.70	0.93	0.93
Man	12	62	221	114	-7.9	90	82	1.27	14.4	0.16	0.14	106	-9.4	89	79	1.20	11.3	0.16	0.15	0.77	0.50	9	2.3	1.09	0.97	0.95
Man	4	69	222	46	-2.0	92	90	0.51	23.1	0.28	0.26	46	-2.0	92	90	0.51	23.1	0.23	0.14	0.00	0.51	8	1.7	0.52	0.83	0.92
Man	1	46	223	52	-2.7	84	81	0.62	19.1	0.34	0.34	52	-2.9	84	81	0.62	17.7	0.34	0.31	0.11	0.51	21	2.7	0.91	0.98	0.88
Man	85	70	224	226	-15.1	104	89	2.17	14.9	0.22	0.21	188	-25.6	104	78	1.80	7.3	0.23	0.20	1.65	0.52	23	4.2	0.92	1.07	0.94
Man	29	4	225	245	-10.1	81	71	3.04	24.3	0.24	0.16	202	-18.0	78	60	2.60	11.3	0.20	0.16	2.52	0.52	26	5.9	0.97	0.83	0.94
Man	49	9	226	193	-4.0	102	98	1.90	48.2	0.40	0.24	180	-11.2	99	88	1.82	16.0	0.29	0.25	1.37	0.53	18	3.1	1.04	0.73	0.93
Man	89	171	227	45	-1.7	78	76	0.58	26.0	0.25	0.20	45	-2.0	78	76	0.57	22.3	0.20	0.19	0.05	0.53	18	5.0	0.95	0.79	0.92
Man	85	17	228	71	-0.7	111	111	0.64	50.0	0.40	0.33	71	-1.0	111	110	0.64	50.0	0.34	0.21	0.11	0.53	35	6.1	0.62	0.86	0.91
Man	1	98	229	52	-4.5	80	75	0.65	11.6	0.27	0.24	51	-4.6	79	75	0.64	10.9	0.26	0.21	0.11	0.54	20	3.8	0.88	0.96	0.90
Man	65	53	230	231	-13.8	87	73	2.65	16.8	0.39	0.25	186	-26.6	84	58	2.21	7.0	0.42	0.34	2.08	0.57	48	5.0	1.34	1.08	0.91
Man	4	76	231	68	-5.9	86	80	0.79	11.5	0.24	0.23	67	-6.2	86	80	0.78	10.8	0.25	0.23	0.22	0.57	16	2.9	1.03	1.07	0.91
Man	30	77	232	92	-2.9	86	84	1.07	31.6	0.14	0.12	90	-3.7	86	83	1.04	24.1	0.14	0.11	0.49	0.58	7	2.0	0.95	0.94	0.95
Man	85	51	233	219	-7.6	106	99	2.06	28.9	0.40	0.26	195	-18.7	104	85	1.87	10.4	0.37	0.29	1.48	0.58	78	12.1	1.13	0.92	0.92
Man	7	15	234	90	-3.5	75	72	1.20	26.1	0.47	0.28	84	-6.5	73	67	1.15	13.0	0.39	0.22	0.61	0.59	54	9.2	0.78	0.83	0.88
Man	94	11	235	95	-7.7	78	71	1.22	12.3	0.37	0.12	90	-8.7	77	68	1.17	10.4	0.41	0.23	0.60	0.62	78	14.0	1.82	1.10	0.94
Man	49	9	236	115	-5.5	103	97	1.13	21.1	0.22	0.19	113	-6.2	102	96	1.10	18.2	0.21	0.17	0.50	0.63	18	3.4	0.92	0.99	0.93
Man	85	96	237	54	-2.4	74	72	0.74	23.0	0.15	0.14	54	-2.6	74	71	0.73	20.5	0.25	0.21	0.11	0.63	20	3.7	1.56	1.67	0.93
Man	87	44	238	96	-1.8	95	93	1.02	50.0	0.23	0.13	95	-2.3	94	92	1.02	41.9	0.19	0.17	0.39	0.63	52	14.5	1.31	0.83	0.95
Man	4	103	239	68	-7.5	75	68	0.90	9.1	0.12	0.11	66	-7.7	75	68	0.87	8.6	0.21	0.12	0.27	0.63	23	5.1	1.17	1.68	0.95
Man	4	105	240	137	-5.5	100	94	1.37	25.0	0.16	0.13	132	-5.9	99	93	1.34	22.3	0.17	0.17	0.72	0.65	13	3.4	1.33	1.05	0.95
Man	68	164	241	79	-0.2	77	77	1.03	50.0	0.25	0.10	79	-0.6	77	76	1.03	50.0	0.26	0.12	0.38	0.65	73	18.5	1.19	1.03	0.95
Man	1	46	242	66	-0.5	86	85	0.77	50.0	0.29	0.29	65	-0.8	86	85	0.76	50.0	0.30	0.26	0.11	0.66	14	2.3	0.90	1.02	0.88
Man	29	38	243	81	-4.5	81	77	0.99	18.1	0.27	0.26	78	-5.2	81	75	0.97	15.1	0.19	0.18	0.33	0.66	22	5.4	0.67	0.70	0.88
Man	49	52	244	107	-0.7	102	101	1.05	50.0	0.13	0.10	106	-1.6	102	100	1.04	50.0	0.17	0.14	0.38	0.67	9	2.2	1.39	1.33	0.96

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	89	111	245	158	-6.6	89	83	1.77	24.1	0.24	0.12	150	-8.0	87	79	1.72	18.7	0.23	0.15	1.10	0.67	87	19.4	1.26	0.95	0.94
Man	79	197	246	69	-2.3	77	75	0.90	30.2	0.16	0.13	69	-2.1	77	75	0.89	32.7	0.18	0.16	0.22	0.68	16	4.3	1.23	1.10	0.93
Man	4	61	247	75	-3.0	83	80	0.91	25.0	0.29	0.22	74	-3.1	83	80	0.90	23.9	0.26	0.21	0.22	0.69	12	1.9	0.96	0.90	0.89
Man	96	37	248	71	-1.9	87	85	0.81	36.9	0.27	0.26	70	-1.9	87	85	0.80	36.7	0.20	0.20	0.11	0.70	8	1.4	0.74	0.75	0.88
Man	64	12	249	116	2.2	81	84	1.43	50.0	0.38	0.34	114	-3.2	80	77	1.42	35.7	0.35	0.21	0.71	0.72	80	13.1	0.61	0.91	0.84
Man	1	111	250	55	-2.2	75	73	0.73	25.3	0.26	0.12	55	-2.2	75	73	0.73	25.3	0.26	0.11	0.00	0.73	46	11.5	0.92	0.97	0.93
Man	51	28	251	61	-12.0	83	71	0.74	5.1	0.13	0.12	61	-12.0	83	71	0.74	5.1	0.26	0.22	0.00	0.74	10	1.9	1.88	2.01	0.94
Man	68	147	252	131	-4.4	112	108	1.17	29.9	0.22	0.21	128	-6.0	112	106	1.14	21.3	0.24	0.18	0.39	0.78	10	2.5	0.90	1.06	0.92
Man	89	181	253	112	-1.6	81	79	1.39	50.0	0.20	0.19	110	-3.9	80	76	1.37	28.0	0.15	0.13	0.60	0.79	14	3.7	0.70	0.78	0.90
Man	87	93	254	252	-14.1	80	66	3.15	17.8	0.27	0.17	202	-24.7	78	54	2.58	8.2	0.27	0.19	2.36	0.79	37	5.5	1.15	1.02	0.90
Man	56	71	255	84	-10.8	100	89	0.85	7.8	0.17	0.15	83	-10.8	99	88	0.84	7.7	0.17	0.16	0.05	0.80	22	5.0	1.06	0.99	0.93
Man	88	206	256	86	-6.4	84	78	1.02	13.5	0.20	0.16	86	-5.2	84	78	1.02	16.5	0.22	0.19	0.22	0.80	13	3.1	1.17	1.09	0.91
Man	44	86	257	60	-3.5	73	70	0.82	17.4	0.18	0.17	60	-3.5	73	70	0.82	17.4	0.18	0.13	0.00	0.82	13	3.4	0.74	0.98	0.89
Man	85	82	258	132	-11.4	92	80	1.44	11.5	0.19	0.15	123	-12.9	90	77	1.37	9.5	0.24	0.18	0.61	0.83	18	3.9	1.20	1.24	0.92
Man	89	181	259	120	-2.3	80	78	1.50	50.0	0.19	0.14	117	-3.8	79	75	1.47	30.5	0.21	0.16	0.66	0.84	30	6.0	1.19	1.06	0.92
Man	8	32	260	77	-3.8	75	72	1.03	20.2	0.20	0.14	77	-3.9	75	72	1.02	19.6	0.23	0.17	0.16	0.87	9	1.4	1.23	1.11	0.91
Man	4	61	261	134	-2.7	78	76	1.71	49.1	0.41	0.30	125	-7.5	77	69	1.62	16.7	0.25	0.20	0.83	0.88	21	3.4	0.66	0.61	0.82
Man	8	41	262	87	-2.2	78	76	1.11	39.7	0.16	0.16	86	-2.3	78	75	1.11	37.9	0.16	0.15	0.22	0.89	10	2.6	0.94	1.00	0.90
Man	4	61	263	111	-6.1	82	76	1.35	18.2	0.22	0.16	108	-6.2	81	75	1.33	17.4	0.26	0.23	0.44	0.91	17	2.5	1.45	1.20	0.90
Man	73	79	264	67	-5.4	73	68	0.91	12.4	0.42	0.23	67	-5.4	73	68	0.91	12.4	0.44	0.18	0.00	0.91	74	9.4	0.76	1.04	0.84
Man	1	37	265	177	-7.1	78	71	2.26	25.0	0.26	0.16	160	-12.0	77	65	2.08	13.3	0.17	0.16	1.32	0.94	13	3.2	0.98	0.67	0.89
Man	5	63	266	157	-6.5	77	70	2.04	24.3	0.44	0.28	141	-11.8	75	64	1.87	12.0	0.30	0.27	1.10	0.94	56	10.3	0.94	0.69	0.82
Man	75	75	267	119	-13.1	86	73	1.39	9.1	0.17	0.14	114	-13.1	85	72	1.34	8.7	0.19	0.18	0.44	0.95	11	2.2	1.25	1.14	0.91
Man	4	76	268	152	-8.7	85	76	1.79	17.4	0.26	0.18	143	-10.5	83	72	1.72	13.6	0.25	0.20	0.83	0.96	85	19.8	1.10	0.95	0.88
Man	84	17	269	138	-3.1	75	72	1.85	44.7	0.17	0.12	135	-4.5	73	69	1.84	30.1	0.17	0.15	0.87	0.98	11	2.9	1.33	0.98	0.91
Man	56	88	270	94	-1.3	83	82	1.14	50.0	0.37	0.30	94	-1.4	83	81	1.13	50.0	0.33	0.20	0.11	1.03	83	12.3	0.65	0.91	0.81
Man	73	56	271	135	-11.9	89	77	1.53	11.3	0.19	0.13	129	-12.9	88	75	1.47	10.0	0.17	0.15	0.50	1.03	27	7.2	1.12	0.92	0.91
Man	32	18	272	102	-14.8	78	63	1.31	6.9	0.42	0.32	97	-15.9	77	61	1.26	6.1	0.36	0.28	0.27	1.04	25	3.1	0.87	0.86	0.78
Man	89	275	273	99	0.5	85	86	1.16	50.0	0.23	0.17	99	0.4	85	85	1.16	50.0	0.23	0.12	0.11	1.05	10	2.5	0.72	0.97	0.88
Man	68	59	274	134	-3.1	80	77	1.68	43.3	0.44	0.43	129	-8.2	78	70	1.66	15.7	0.31	0.22	0.60	1.08	32	8.2	0.50	0.70	0.73
Man	9	26	275	117	-2.4	77	75	1.52	49.4	0.11	0.10	116	-2.6	76	74	1.52	45.4	0.15	0.15	0.44	1.08	9	2.5	1.46	1.40	0.92
Man	5	64	276	131	-3.4	84	81	1.56	38.9	0.22	0.19	129	-4.4	84	80	1.53	29.4	0.21	0.14	0.44	1.12	17	3.6	0.70	0.97	0.86
Man	76	118	277	131	-2.2	75	73	1.76	50.0	0.20	0.16	128	-4.6	75	70	1.72	27.6	0.17	0.12	0.61	1.15	13	4.1	0.72	0.89	0.86
Man	68	125	278	161	-3.0	98	95	1.65	50.0	0.24	0.22	159	-4.3	98	93	1.63	37.1	0.18	0.12	0.50	1.15	21	5.3	0.55	0.73	0.85
Man	88	206	279	130	-5.5	89	84	1.45	23.7	0.31	0.28	128	-6.4	89	83	1.43	20.1	0.41	0.14	0.22	1.23	37	4.9	0.50	1.35	0.80

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Man	9	81	280	136	-8.9	84	75	1.61	15.2	0.23	0.20	132	-9.8	83	73	1.59	13.4	0.20	0.19	0.38	1.23	67	16.6	0.95	0.87	0.84
Man	7	68	281	144	-11.6	83	71	1.74	12.5	0.25	0.25	137	-12.9	82	69	1.67	10.6	0.19	0.18	0.50	1.24	20	4.4	0.72	0.78	0.81
Man	66	268	282	262	-10.6	76	66	3.44	24.8	0.32	0.16	226	-21.0	74	53	3.05	10.8	0.28	0.25	2.20	1.24	51	9.2	1.57	0.88	0.86
Man	4	44	283	222	-24.2	99	75	2.24	9.2	0.26	0.25	191	-27.9	98	70	1.96	6.9	0.23	0.19	0.99	1.25	15	2.9	0.77	0.88	0.83
Man	76	4	284	109	-4.6	80	75	1.37	24.0	0.18	0.16	109	-4.8	79	74	1.37	22.5	0.20	0.20	0.11	1.26	12	2.8	1.21	1.13	0.86
Man	8	47	285	198	-9.9	82	72	2.41	19.9	0.31	0.18	181	-13.7	79	66	2.29	13.2	0.25	0.21	1.15	1.26	28	4.5	1.16	0.83	0.85
Man	89	276	286	153	1.2	73	74	2.09	50.0	0.27	0.25	151	-3.7	73	70	2.06	40.3	0.16	0.14	0.77	1.32	15	3.9	0.55	0.60	0.78
Man	4	57	287	122	-14.7	75	61	1.62	8.3	0.33	0.13	118	-14.7	75	60	1.58	8.0	0.24	0.18	0.27	1.35	30	6.7	1.40	0.72	0.87
Man	21	1	288	151	0.5	77	77	1.97	50.0	0.27	0.18	149	-2.9	76	73	1.96	50.0	0.23	0.19	0.61	1.36	9	1.4	1.02	0.84	0.83
Man	87	179	289	181	-17.4	110	93	1.65	10.4	0.14	0.12	175	-18.4	109	91	1.60	9.5	0.13	0.12	0.28	1.37	6	1.6	0.96	0.97	0.91
Man	22	15	290	126	-5.9	74	68	1.70	21.2	0.35	0.29	123	-6.8	73	66	1.67	18.0	0.34	0.22	0.33	1.37	74	14.2	0.78	0.95	0.75
Man	96	37	291	175	-15.6	102	86	1.72	11.2	0.21	0.21	170	-16.7	102	85	1.66	10.2	0.15	0.12	0.33	1.39	7	1.6	0.57	0.71	0.84
Man	66	334	292	171	-10.6	75	64	2.29	16.2	0.30	0.11	161	-12.0	74	62	2.17	13.4	0.17	0.17	0.88	1.41	10	2.4	1.51	0.58	0.88
Man	7	59	293	276	-3.1	85	82	3.24	50.0	0.20	0.17	254	-10.3	82	72	3.09	24.6	0.14	0.13	1.81	1.43	19	5.9	0.76	0.70	0.84
Man	4	100	294	128	-8.5	75	66	1.71	15.1	0.16	0.13	124	-8.9	75	66	1.66	13.9	0.18	0.14	0.27	1.44	15	4.3	1.07	1.11	0.86
Man	81	21	295	190	-7.2	74	67	2.56	26.5	0.13	0.11	179	-9.9	73	63	2.44	18.0	0.14	0.12	0.99	1.57	14	4.2	1.06	1.10	0.87
Man	89	142	296	159	-10.1	90	80	1.77	15.7	0.32	0.16	158	-10.1	89	79	1.77	15.6	0.19	0.16	0.11	1.66	27	8.1	1.00	0.59	0.84
Man	1	37	297	160	-9.0	82	73	1.95	17.8	0.20	0.20	156	-9.9	82	72	1.91	15.8	0.16	0.14	0.27	1.68	10	2.3	0.66	0.80	0.79
Man	76	31	298	194	-3.6	76	73	2.54	50.0	0.43	0.34	186	-10.8	75	65	2.46	17.1	0.37	0.19	0.82	1.72	45	8.1	0.56	0.85	0.67
Man	79	25	299	179	-10.1	82	72	2.18	17.7	0.20	0.17	174	-11.8	82	70	2.12	14.7	0.18	0.17	0.39	1.79	18	4.3	1.01	0.91	0.81
Man	27	49	300	199	-26.2	82	56	2.42	7.6	0.15	0.12	185	-26.5	81	55	2.28	7.0	0.18	0.17	0.50	1.92	18	4.2	1.45	1.22	0.85
Man	52	20	301	188	-13.1	77	64	2.45	14.3	0.16	0.13	182	-14.5	77	62	2.37	12.6	0.16	0.13	0.38	2.07	12	3.0	0.96	0.98	0.81
Man	1	37	302	224	-12.7	84	72	2.65	17.7	0.48	0.33	222	-12.9	84	71	2.63	17.3	0.32	0.20	0.11	2.54	86	15.5	0.62	0.68	0.61
Man	66	157	303	354	-10.2	100	90	3.52	34.7	0.24	0.17	345	-11.5	100	88	3.46	30.1	0.21	0.11	0.66	2.86	47	9.7	0.69	0.86	0.77
Acc	66	79	1	150	3.2	80	83	1.87	50.0	0.30	0.14	123	-13.7	78	65	1.56	9.0	0.33	0.25	4.07	-2.20	80	14.4	1.75	1.08	1.33
Acc	93	69	2	131	-4.2	93	89	1.40	31.1	0.16	0.12	104	-12.5	89	77	1.17	8.4	0.16	0.14	3.02	-1.62	12	3.5	1.11	1.01	1.16
Acc	21	70	3	106	5.0	82	87	1.29	50.0	0.35	0.14	96	-11.0	80	69	1.21	8.7	0.41	0.33	2.69	-1.40	24	2.9	2.39	1.18	1.18
Acc	61	44	4	103	4.1	100	104	1.04	50.0	0.16	0.13	100	-3.3	100	96	1.01	30.6	0.13	0.13	2.31	-1.27	21	6.2	1.02	0.84	1.12
Acc	85	66	5	107	1.5	89	91	1.19	50.0	0.42	0.31	79	-21.5	90	69	0.87	3.7	0.50	0.46	2.25	-1.06	59	6.2	1.45	1.18	1.31
Acc	65	66	6	120	-5.6	78	72	1.54	21.6	0.45	0.14	93	-13.9	75	62	1.23	6.7	0.44	0.27	2.47	-0.93	42	4.7	1.91	0.97	1.12
Acc	88	186	7	117	-4.0	87	83	1.35	29.3	0.37	0.18	91	-16.6	84	67	1.08	5.5	0.41	0.41	2.14	-0.79	48	6.1	2.23	1.11	1.12
Acc	14	24	8	95	-13.3	83	70	1.14	7.1	0.19	0.18	62	-18.9	79	60	0.78	3.3	0.30	0.30	1.92	-0.78	21	3.0	1.68	1.62	1.12
Acc	87	116	9	106	-2.7	111	109	0.95	38.9	0.28	0.23	90	-11.8	111	99	0.81	7.7	0.20	0.17	1.70	-0.75	13	2.5	0.75	0.73	1.11
Acc	81	36	10	118	-2.3	92	89	1.29	50.0	0.22	0.17	100	-12.9	92	79	1.09	7.8	0.25	0.22	2.03	-0.74	18	3.4	1.33	1.17	1.10
Acc	59	66	11	66	-6.4	85	79	0.78	10.4	0.44	0.22	50	-13.9	82	68	0.60	3.6	0.46	0.38	1.48	-0.70	43	3.7	1.73	1.05	1.13

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT,s	Htm-WT,s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Acc	87	192	12	204	-11.7	102	90	2.00	17.5	0.35	0.26	148	-24.9	100	75	1.48	5.9	0.38	0.18	2.64	-0.64	48	6.4	0.69	1.09	1.12
Acc	52	23	13	96	-0.5	98	98	0.98	50.0	0.23	0.22	85	-9.5	98	88	0.87	9.0	0.16	0.15	1.48	-0.50	11	2.5	0.69	0.71	1.08
Acc	4	100	14	93	-2.0	87	85	1.07	46.5	0.28	0.17	81	-7.0	85	78	0.95	11.5	0.22	0.21	1.48	-0.41	86	25.1	1.20	0.79	1.06
Acc	89	245	15	115	-7.7	107	99	1.08	15.0	0.33	0.20	96	-14.5	106	91	0.91	6.6	0.34	0.30	1.48	-0.40	38	4.9	1.53	1.05	1.05
Acc	21	40	16	69	-1.8	78	77	0.88	37.8	0.25	0.23	61	-7.8	77	69	0.80	7.8	0.31	0.31	1.10	-0.22	27	6.7	1.31	1.24	1.04
Acc	66	94	17	180	-13.2	95	81	1.91	13.7	0.29	0.25	133	-25.6	92	66	1.45	5.2	0.24	0.24	2.09	-0.18	15	2.7	0.94	0.84	1.03
Acc	88	207	18	79	-2.5	86	83	0.92	32.1	0.33	0.24	71	-7.8	84	76	0.85	9.1	0.32	0.32	1.10	-0.18	21	3.5	1.32	0.96	1.03
Acc	85	69	19	54	2.7	92	94	0.59	50.0	0.38	0.38	52	-3.4	90	87	0.57	15.3	0.29	0.28	0.71	-0.12	14	2.2	0.72	0.76	1.03
Acc	66	53	20	235	-7.6	79	72	2.96	31.0	0.44	0.22	177	-26.3	77	51	2.30	6.7	0.36	0.31	3.07	-0.11	49	5.5	1.41	0.82	1.02
Acc	43	33	21	112	-9.2	79	70	1.41	12.2	0.28	0.25	91	-15.8	77	61	1.19	5.8	0.33	0.30	1.49	-0.08	66	14.8	1.19	1.20	1.02
Acc	89	51	22	146	-0.5	106	106	1.37	50.0	0.38	0.37	130	-14.0	105	91	1.24	9.3	0.27	0.23	1.43	-0.06	22	3.5	0.61	0.71	1.01
Acc	76	64	23	262	-3.0	89	86	2.93	50.0	0.37	0.16	231	-14.3	86	71	2.70	16.2	0.32	0.17	2.91	0.02	76	19.6	1.07	0.88	1.00
Acc	96	90	24	108	-2.6	100	97	1.08	42.3	0.27	0.27	99	-10.0	100	90	0.99	9.9	0.15	0.10	0.99	0.09	7	1.6	0.37	0.54	0.98
Acc	80	27	25	32	-4.6	81	76	0.40	7.1	0.35	0.23	31	-5.5	81	75	0.38	5.6	0.28	0.18	0.28	0.12	81	19.0	0.77	0.79	0.98
Acc	89	259	26	74	-1.3	85	84	0.87	50.0	0.37	0.27	70	-5.9	85	79	0.82	11.7	0.41	0.29	0.72	0.15	17	2.4	1.07	1.10	0.97
Acc	89	276	27	76	0.5	87	88	0.87	50.0	0.34	0.29	73	-4.6	86	81	0.85	15.7	0.32	0.29	0.71	0.16	47	7.0	0.99	0.92	0.97
Acc	66	270	28	157	-3.9	80	76	1.96	40.0	0.23	0.20	136	-14.8	79	64	1.72	9.2	0.21	0.17	1.76	0.20	21	4.0	0.84	0.91	0.97
Acc	81	176	29	125	-0.3	109	109	1.14	50.0	0.15	0.15	122	-2.8	109	106	1.13	43.3	0.17	0.17	0.94	0.20	11	2.8	1.12	1.16	0.98
Acc	41	54	30	118	-7.2	104	97	1.13	16.4	0.24	0.23	108	-12.3	103	91	1.05	8.8	0.17	0.14	0.82	0.31	37	9.6	0.61	0.71	0.96
Acc	44	149	31	213	-6.9	85	78	2.50	30.7	0.55	0.29	169	-25.5	84	59	2.01	6.6	0.46	0.32	2.19	0.31	76	8.8	1.08	0.85	0.93
Acc	89	230	32	169	-3.5	101	98	1.67	48.8	0.18	0.11	161	-6.7	100	93	1.62	23.9	0.18	0.18	1.32	0.35	14	3.3	1.66	1.00	0.98
Acc	54	107	33	166	-6.8	87	80	1.90	24.2	0.20	0.12	151	-12.2	86	74	1.76	12.3	0.18	0.13	1.54	0.36	7	2.1	1.08	0.87	0.97
Acc	88	165	34	119	0.0	95	95	1.26	50.0	0.18	0.12	118	-1.9	94	92	1.25	50.0	0.14	0.13	0.88	0.38	10	3.1	1.08	0.79	0.97
Acc	65	66	35	74	-1.5	78	76	0.95	47.6	0.34	0.29	72	-3.5	77	73	0.93	20.7	0.27	0.23	0.50	0.45	11	1.7	0.79	0.79	0.90
Acc	21	48	36	125	-4.6	85	80	1.47	27.4	0.25	0.24	116	-10.3	84	74	1.37	11.2	0.26	0.21	0.99	0.48	15	2.8	0.86	1.03	0.92
Acc	46	104	37	184	-0.7	96	95	1.91	50.0	0.29	0.21	172	-9.9	95	85	1.80	17.3	0.25	0.20	1.43	0.48	29	4.8	0.95	0.88	0.94
Acc	88	206	38	81	-4.2	111	107	0.73	19.4	0.20	0.20	80	-4.5	110	106	0.73	18.0	0.25	0.25	0.22	0.51	21	3.3	1.26	1.22	0.94
Acc	29	23	39	114	-6.1	91	85	1.25	18.6	0.40	0.28	105	-9.2	89	79	1.19	11.4	0.44	0.40	0.71	0.54	54	13.7	1.45	1.11	0.90
Acc	22	98	40	60	-4.9	74	69	0.82	12.3	0.35	0.16	59	-5.1	73	68	0.81	11.6	0.25	0.17	0.22	0.60	75	14.7	1.05	0.73	0.92
Acc	56	34	41	108	-1.2	98	97	1.10	50.0	0.36	0.11	106	-2.0	98	96	1.09	50.0	0.29	0.12	0.49	0.61	40	9.3	1.11	0.80	0.96
Acc	89	263	42	85	-6.5	95	88	0.89	13.1	0.36	0.36	81	-8.8	95	86	0.86	9.2	0.30	0.28	0.28	0.61	19	2.8	0.78	0.86	0.87
Acc	92	40	43	128	1.1	103	104	1.24	50.0	0.27	0.27	126	-1.8	102	100	1.24	50.0	0.19	0.16	0.61	0.63	16	3.4	0.60	0.70	0.90
Acc	75	68	44	134	-2.6	77	74	1.74	50.0	0.15	0.15	128	-5.9	75	70	1.70	21.6	0.18	0.17	1.10	0.64	15	3.7	1.17	1.15	0.93
Acc	47	42	45	158	-1.9	78	77	2.02	50.0	0.20	0.17	150	-7.7	78	70	1.93	19.4	0.20	0.18	1.32	0.70	32	7.1	1.03	0.98	0.91
Acc	78	129	46	81	-3.1	99	96	0.82	26.3	0.31	0.31	81	-3.3	99	96	0.82	24.7	0.18	0.18	0.11	0.71	12	2.4	0.58	0.59	0.87

Table E-1. Response to braking

				Preceding Vehicle Intersection								Acc Vehicle Intersection								Wait time, ratios and brake appl. time numerics						
Cntrl	Drv	Trip	#	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	Rng, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Tti, s	Max Ax, g	M2, g	WT, s	Htm-WT, s	ΔV, ft/s	ΔT, s	Slope Ratio	Max Ratio	Est. Ax Ratio
Acc	89	67	47	135	-4.4	91	86	1.49	31.0	0.35	0.24	129	-7.7	89	81	1.46	16.9	0.34	0.33	0.77	0.72	39	6.7	1.36	0.96	0.89
Acc	76	89	48	375	-13.7	86	73	4.34	27.5	0.26	0.13	294	-29.5	86	57	3.40	10.0	0.21	0.18	3.57	0.77	28	5.3	1.35	0.79	0.93
Acc	5	60	49	81	-3.9	81	77	1.00	20.7	0.26	0.26	80	-4.4	81	76	0.99	18.2	0.24	0.22	0.22	0.78	24	5.1	0.85	0.93	0.86
Acc	11	47	50	128	-15.9	79	63	1.62	8.1	0.27	0.19	113	-17.8	78	60	1.45	6.4	0.30	0.27	0.82	0.80	42	7.3	1.44	1.09	0.89
Acc	89	66	51	182	-1.9	88	86	2.07	50.0	0.27	0.18	175	-6.7	86	80	2.02	26.3	0.21	0.19	1.26	0.81	25	4.8	1.01	0.81	0.90
Acc	6	50	52	94	-8.0	86	78	1.09	11.7	0.14	0.12	92	-7.7	86	78	1.07	12.0	0.24	0.22	0.27	0.82	16	3.2	1.94	1.64	0.93
Acc	73	167	53	161	-5.5	102	96	1.58	29.5	0.19	0.17	156	-7.5	101	94	1.54	20.9	0.19	0.15	0.71	0.87	24	5.7	0.85	1.00	0.91
Acc	92	62	54	225	-0.3	102	102	2.21	50.0	0.19	0.15	219	-5.1	100	95	2.18	42.9	0.16	0.14	1.21	1.00	15	4.5	0.94	0.85	0.91
Acc	90	183	55	272	-2.4	89	86	3.07	50.0	0.30	0.18	252	-12.8	88	75	2.86	19.7	0.27	0.14	2.03	1.04	34	7.0	0.78	0.89	0.88
Acc	25	39	56	139	-0.4	84	84	1.65	50.0	0.28	0.24	135	-2.6	84	81	1.62	50.0	0.19	0.16	0.50	1.15	12	3.3	0.66	0.68	0.83
Acc	21	42	57	131	-1.1	86	85	1.52	50.0	0.30	0.29	130	-2.6	86	84	1.51	49.3	0.24	0.19	0.33	1.19	18	4.0	0.64	0.80	0.80
Acc	92	62	58	235	-2.5	110	108	2.13	50.0	0.22	0.22	230	-5.3	109	104	2.10	43.4	0.18	0.10	0.82	1.31	15	4.0	0.47	0.82	0.86
Acc	76	155	59	268	-26.4	89	63	3.00	10.2	0.45	0.29	212	-41.1	89	48	2.37	5.1	0.49	0.46	1.54	1.46	42	4.3	1.57	1.09	0.76
Acc	92	94	60	173	-8.4	103	95	1.67	20.6	0.36	0.14	172	-8.6	103	95	1.66	20.0	0.28	0.16	0.05	1.62	74	16.4	1.15	0.79	0.88
Acc	56	79	61	207	-20.0	91	71	2.28	10.4	0.28	0.22	189	-22.9	90	67	2.10	8.3	0.32	0.20	0.66	1.62	42	6.7	0.92	1.17	0.80
Acc	40	54	62	226	-4.4	100	95	2.27	50.0	0.20	0.16	221	-7.1	100	93	2.22	31.4	0.18	0.17	0.61	1.66	12	2.7	1.05	0.88	0.85
Acc	89	111	63	159	-6.2	94	88	1.70	25.7	0.30	0.24	159	-6.2	94	88	1.70	25.7	0.29	0.23	0.00	1.70	31	5.1	0.94	0.96	0.78
Acc	96	76	64	170	-11.7	99	87	1.72	14.6	0.28	0.26	170	-11.7	99	87	1.72	14.6	0.23	0.19	0.00	1.72	32	6.2	0.72	0.85	0.77
Acc	6	44	65	289	-13.3	93	80	3.10	21.7	0.15	0.10	265	-16.9	92	75	2.87	15.7	0.17	0.14	1.32	1.78	23	5.8	1.39	1.08	0.89
Acc	4	99	66	215	-30.2	105	75	2.05	7.1	0.22	0.22	206	-30.5	104	74	1.98	6.8	0.32	0.28	0.22	1.83	33	4.2	1.26	1.45	0.80
Acc	76	89	67	260	-13.5	87	74	2.98	19.3	0.32	0.14	250	-15.3	86	70	2.91	16.3	0.19	0.15	0.61	2.37	42	9.0	1.07	0.60	0.81

APPENDIX F

Final NHTSA Algorithm Code

This appendix lists the computer code (written in Microsoft Visual Basic using Visual Studio version 6.0) that perform data processing for FCW analysis purposes. This code receives a "Kalmanized" data set (see section 5.4), and processes it to determine whether a forward collision warning is to be issued.

```
Sub doNHTSAWarning()
On Error GoTo Routine_Error
```

' declare all variables

```
Dim npts As Long, i As Long
Dim VDotNHTSA As Single, Rmin As Single, Rdot20 As Single
Dim R0 As Single, Rdot0 As Single, V0 As Single, Vdot0 As Single, Vpdot0 As
    Single
Dim RdotTd As Single, VTd As Single, Ts As Single, Tnhtsa As Single, Rnhtsa As
    Single
Dim Tsp As Single, dR As Single, Vp0 As Single, Trdots As Single, Rdot2Td
Dim warning As Integer, count As Long
Dim warnDur As Integer, k As Long, flag As Boolean, DoneFlag As Boolean
' set parameter values
warnDur = 3
VDotNHTSA = -0.75 * 32.2
Rmin = 7#
```

'Query the Kalman and Time history database for data

```
Set rstTarget = dbsTarget.OpenRecordset("select * from " & nhtsaName & ";")

fldstr = " SELECT R_Kal, Rdot_Kal, V_Kal, Vdot_Kal, " & _
" VpDot_Kal, Glitch_Kal, KalmanResults.Count, 0 as Warning, Brake, 0.0 AS VcDot
    "
frmstr = " FROM KalmanResults INNER JOIN TimeHistory ON " & _
" (KalmanResults.Count = TimeHistory.Count) AND " & _
" (KalmanResults.TripId = TimeHistory.TripID) AND " & _
" (KalmanResults.DriverId = TimeHistory.DriverId) AND " & _
" (KalmanResults.EventId = TimeHistory.EventId) "
whrstr = " Where KalmanResults.DriverId = " & DriverId & " And
    KalmanResults.TripID = " & TripID & _
" And KalmanResults.EventId = " & EventId & " ORDER BY KalmanResults.Time "
sqlstr = fldstr & frmstr & whrstr & " ;"
Set rstNHTSA = dbsTarget.OpenRecordset(sqlstr, dbOpenSnapshot)
```

' check validity of recordset and dump to array if okay

```
If IsValidRecordset(rstNHTSA) Then
    rstNHTSA.MoveLast
    npts = rstNHTSA.RecordCount
    rstNHTSA.MoveFirst
    varArray = rstNHTSA.GetRows(npts)
    rstNHTSA.Close
    DoneFlag = False
    'loop thru the data
    For i = 0 To npts - 1
      If CSng(varArray(3, i)) < -CSng(varArray(2, i)) / Td Then
        varArray(7, i) = 0
        GoTo Continue
```

```
      End If
      If CSng(varArray(2, i)) <= 0# Then
        varArray(7, i) = 0
        GoTo Continue
      End If
      'set some initial values
        count = CInt(varArray(6, i))
        R0 = CSng(varArray(0, i))
        Rdot0 = CSng(varArray(1, i))
        V0 = CSng(varArray(2, i))
        Vdot0 = CSng(varArray(3, i))
        Vpdot0 = CSng(varArray(4, i))
        Rdot20 = Vpdot0 - Vdot0
        RdotTd = Rdot0 + Td * Rdot20
        dR = 0#
        Vp0 = V0 + Rdot0
        If (RdotTd >= 0 And Rdot0 >= 0) Then GoTo Continue
        If CInt(varArray(5, i)) = 1 Then GoTo Continue
        VTd = V0 + Td * Vdot0
        Ts = -VTd / VDotNHTSA
        Tnhtsa = Ts + Td
        Rnhtsa = ((V0 + VTd) / 2#) * Td + (VTd / 2#) * Ts
        If Vp0 <= 0# Then
          Tsp = 0#
        ElseIf (Vpdot0 > -0.01) Then
          Tsp = 50#
        Else
          Tsp = -Vp0 / Vpdot0
        End If

        If Vp0 <= 0# Then
          dR = Rnhtsa
        ElseIf (Tsp < Tnhtsa) Then
          dR = Rnhtsa - (Vp0 / 2#) * Tsp
        ElseIf (RdotTd > 0 And Rdot0 < 0) Then
          If Rdot20 = 0 Then
            MsgBox "stop rdot20 is zero"
          Else
            Trdots = -Rdot0 / Rdot20
          End If
          dR = -(Rdot0 / 2#) * Trdots
        ElseIf (RdotTd < 0 And (Vp0 + Vpdot0 * Tnhtsa) > 0) Then
          Rdot2Td = Vpdot0 - VDotNHTSA
          If Rdot2Td = 0 Then
            MsgBox "stop rdot2td is zero"
          Else
            Trdots = -RdotTd / Rdot2Td
          End If
          dR = -(((Rdot0 + RdotTd) / 2#) * Td + (RdotTd / 2#) * Trdots)
        Else
          MsgBox ("Data slipped through")
        End If




Continue:
If R0 <= dR + Rmin And varArray(5, i) = 0 Then
            varArray(7, i) = 1
          Else
```

```
            varArray(7, i) = 0
          End If
          'check for three warnings in a row
          If i >= warnDur And CInt(varArray(7, i)) = 1 Then
            flag = True
            For k = i - 1 To i - (warnDur - 1) Step -1
              If CInt(varArray(7, k)) < 1 Then flag = False
            Next k
            If flag And Not DoneFlag Then
              varArray(7, i) = 2
              DoneFlag = True
            End If
          End If

    Next i
    'rewright the array to simplify things
    For i = 0 To npts - 1
      If varArray(7, i) = 2 Then
        varArray(7, i) = 1
      Else
        varArray(7, i) = 0
      End If
    Next i

Else
    rstNHTSA.Close
End If
```

'load a table with the results

```
For i = 0 To npts - 1
  rstTarget.AddNew
  rstTarget!DriverId = DriverId
  rstTarget!TripID = TripID
  rstTarget!EventId = EventId
  rstTarget!count = CLng(varArray(6, i))
  rstTarget!warning = CInt(varArray(7, i))
  rstTarget.Update
Next i

rstTarget.Close

Routine_Done:
Routine_Exit:
Exit Sub
Routine_Error:
    Select Case Err.Number
    Case Else
    Call updateLog(dbsTarget, "Error-in sub doNHTSAWarning " & _
    "Error = " & Err.Number & " " & Err.Description)
    End Select
Resume Routine_Exit
End Sub
```

APPENDIX G

This appendix lists the MATLAB™ computer code of the Kalman filter discussed in section 5.4. It includes also a discussion about how certain data anomalies (glitches) were handled.

```
% Kalman filter of FOT data streams. The filter receives raw FOT
% data, and returns smooth, "Kalmanized" data.
% Adjust the diagonal elements of R and/or Q to "tune" the filter.

dt = 0.10;        % time step

%--------------------------------------------------------------
% The data file (named FILENAME)is space-delimited ascii file,
% and each line should contains the following:
%       t          (time)
%       R          (Range)
%       Rdot       (Range rate)
%       V          (Speed)
%--------------------------------------------------------------
load FILENAME -ascii;          % replace FILENAME with the actual name
fid = fopen('NEWNAME','w');    % replace NEWNAME with a name of a file
                               % to export Kalman results

theData = FILENAME;            % assign the data you read from FILENAME
                               % to the variable called "theData"

% parse theData into variables:
t    = theData(:,1);       % Rdot
R    = theData(:,2);       % R
Rdot = theData(:,3);       % Rdot
V    = theData(:,4);       % V

% Setup Kalman filer Model and Covariance Matrices
%--------------------------------------------------------------
% The state-variables vector:
%       R
%       Rdot
%       V
%       Vdot
%       VpDot
%--------------------------------------------------------------

A = [  0  1  0  0  0
       0  0  0 -1  1
       0 -1  0  0  1
       0  0  0  0  0
       0  0  0  0  0 ];

C = [  1  0  0  0  0
       0  1  0  0  0
       0  0  1  0  0 ];

PHI = [   1 dt   0 -dt^2/2  dt^2/2
          0  1   0 -dt       dt
          0  0   1  dt        0
          0  0   0  1         0
          0  0   0  0         1    ];
```

```
Q = eye(5)*0.25;
P = Q;

RR = [ 2.25 0    0          % Range measurment
       0    1.9  0          % Range-rate measurment
       0    0    2.15];     % V measurement

RR = RR * 1;

% Initialize State:
   xhat  = [  R(1)
             Rdot(1)
              V(1)
               0
               0 ];

   xbar = xhat;

% Start of Time Loop (k counter): ----------------------------

% Load Measurment Vector z with measurements:

for k=1:length(t),

   y(1) = R(k);      % Range measurment
   y(2) = Rdot(k);   % Range-rate measurment
   y(3) = V(k);      % V measurement

   % glitch-handling should be inserted here per the writeup.
   % for clarity purposes it is not included in this code.

% The Kalman Filer:

% Extrapolate covariance
P = PHI*P*PHI' + Q;

% Kalman gain matrix:
L = P*C'/(C*P*C' + RR);

% perform the Kalman best-estimate:
xhat = xbar + L*(y' - C*xbar);

% time updates for state & caovariance (for next time step):
xbar = PHI * xhat;

P = (eye(5) - L*C)*P;

% save Kalman outputs:
   out(k, 1) = xhat(1);    % R
   out(k, 2) = xhat(2);    % Rdot
   out(k, 3) = xhat(3);    % V
   out(k, 4) = xhat(4);    % Vdot
   out(k, 5) = xhat(5);    % VpDot

% export the Kalman data
   fprintf(fid1,'%f %f %f %f %f\r',xhat(1),xhat(2),xhat(3),xhat(4),xhat(5));

end
% End of Time Loop (k counter): -------------------------------

fclose(fid);               % now that we're done - close the output file.
```

Glitch Handling

Several idiosyncrasies associated with the particular ACC-with-brakes hardware that was used in the FOCAS program introduced the need for occasional special data-handling routines. In specific terms, the information provided by the IR sensors and by the vehicle had some special anomalies. These anomalies, or *glitches*, had to be addressed when processing the data using the Kalman filter. Examples of such glitches include, but were not limited to the following:

- momentary drops in the velocity data from the vehicle
- momentary drops in the range and range-rate data from the sensors
- sudden changes in range data when the sensors "jumped" from one target to another
- when the sensors changes targets, the special differentiation algorithm that computed range-rate (part of the sensor), could report abnormal values

When data were post-processed so that at any time t future values at t+n (as well as past values at t-m) might be taken into account, these glitches could be resolved relatively easily. That is, for example, if at one point the sensor stopped reporting a target, one could look forward in time in the data to see if a qualified target (one that is within some range and range-rate boundaries) re-appears, and to conclude that it's the same object that the sensors lost at the point in question. However, when developing the Kalman filter algorithm which is aimed at operating in the vehicle at real time, we no longer have the ability to look at the future, and provisions must be made to deal with each glitch as it presents itself.

The approach employed in the design of the Kalman filter assessed each glitch. Depending on the situation and the type of data, germane rules were constructed to deal with each glitch. Using terminology presented in the discussion of the Kalman filter, the following table summarizes this set of rules.

Glitch type/source	Handling routine
Glitched velocity data	if the velocity information is unusual (data point that indicates physical impossibility), disregard the data and "pretend" that the model's output is the actual data ($\tilde{y}_n = C \cdot \bar{x}_n$) and initialize[1]
Glitched range	if the combination of range, range-rate, and velocity information is unusual (data point that indicates some "phantom" target, very close in front of the car), disregard the data and "pretend" that the model's output is the actual data ($\tilde{y}_n = C \cdot \bar{x}_n$) and initialize
Lost or Invalid target	if while following a target, the data indicate that it has suddenly disappeared or became invalid (by means of a special qualifier in the data), then we accept the data (we do not "pretend") and initialize
New target	if the data indicate that a new target has appeared (by means of a special qualifier in the data), then we accept the data (we do not "pretend") and initialize

[1] When we initialize the Kalman filter, we use the data read at that point as a set of initial conditions, and continue to calculations from that point. Specifically, if resetting at point k, then $\bar{x}_k = \mathrm{DataSet}_k$, and $\hat{x}_k = \bar{x}_k$. The covariance matrix P, however, which is a cumulative statistical qualifier of the data, is carried over and does not revert to its initial-conditions value. The objective of initializing is to rapidly bring the Kalman filer to the new data point and continue on while avoiding the inherent delay of the model when the filter needs to "traverse" large data disparities.

APPENDIX H

BRAKE EVENT TABLE

This appendix contains Table H-1. This table lists statistics on all captured brake events in the ICC FOT.

Table H-1. FOT Brake Events

				Preceding Vehicle "Brake On"						Acc Vehicle Brake On						Event Minimums						ΔT & V		Warnings			Severity	
Ctrl	[illegible]	[illegible]	[illegible]	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Hm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	29	47	1	177	-16	93	77	1.9	11	100	-19	88	69	1.1	5	-0.17	-0.15	56	-21	0.8	5	5.1	-18	0	1	1	-0.10	-0.11
Man	29	1	2	77	6	86	91	0.9	50	72	-3	84	82	0.9	27	-0.22	-0.28	62	-6	0.8	10	4.4	-20	0	1	0	-0.05	-0.18
Man	89	114	3	44	3	84	87	0.5	50	41	-4	82	78	0.5	10	-0.23	-0.17	37	-6	0.5	7	1.7	-10	0	0	0	-0.05	-0.01
Man	88	8	4	170	5	85	90	2.0	50	146	-16	85	69	1.7	9	-0.37	-0.32	106	-17	1.7	8	6.7	-41	0	1	0	-0.15	-0.23
Man	96	19	5	139	1	103	105	1.3	50	119	-9	103	94	1.2	14	-0.14	-0.15	105	-9	1.1	13	2.7	-10	0	0	0	-0.05	-0.11
Man	9	23	6	101	-2	79	78	1.3	50	75	-12	78	66	1.0	6	-0.16	-0.21	55	-13	0.8	5	2.5	-10	0	1	1	-0.05	-0.17
Man	68	9	7	156	-6	98	93	1.6	28	129	-17	95	79	1.3	8	-0.25	-0.27	77	-21	1.0	5	4.0	-18	0	1	1	-0.10	-0.25
Man	81	163	8	122	1	89	90	1.4	50	106	-12	88	76	1.2	9	-0.56	-0.56	60	-20	1.1	4	4.6	-39	0	1	1	-0.20	-0.39
Man	88	1	9	110	2	89	92	1.2	50	101	-6	89	82	1.1	16	-0.11	-0.14	93	-7	1.1	13	1.8	-6	0	0	0	-0.05	-0.11
Man	88	1	10	102	1	96	97	1.1	50	100	-2	95	93	1.0	42	-0.20	-0.23	83	-9	1.0	10	3.4	-11	0	1	0	-0.05	-0.18
Man	89	142	11	203	-3	100	97	2.0	50	175	-15	96	81	1.8	12	-0.29	-0.22	139	-16	1.7	10	3.8	-21	0	1	0	-0.15	-0.17
Man	4	69	12	127	-5	101	96	1.3	25	102	-13	99	86	1.0	8	-0.36	-0.33	69	-17	0.9	5	3.4	-24	0	1	1	-0.10	-0.25
Man	66	334	13	140	-3	94	91	1.5	47	126	-9	92	83	1.4	14	-0.21	-0.19	76	-13	1.1	8	5.9	-30	0	1	0	-0.10	-0.16
Man	31	33	14	84	-2	90	88	0.9	37	79	-5	89	84	0.9	16	-0.16	-0.13	69	-6	0.9	14	3.5	-12	0	0	0	-0.05	-0.10
Man	73	181	15	35	1	75	76	0.5	50	28	-6	75	69	0.4	5	-0.30	-0.24	21	-7	0.3	4	3.0	-16	1	1	1	-0.10	-0.16
Man	92	47	16	138	2	95	97	1.5	50	107	-19	95	76	1.1	6	-0.14	-0.30	84	-19	1.0	6	2.0	-7	0	1	1	-0.05	-0.28
Man	52	48	17	62	-8	80	72	0.8	7	40	-16	78	62	0.5	2	-0.23	-0.37	31	-20	0.4	2	1.8	-10	1	1	1	-0.05	-0.34
Man	52	52	18	170	-11	97	86	1.8	16	138	-19	97	78	1.4	7	-0.19	-0.18	60	-21	0.8	5	5.6	-25	0	1	1	-0.10	-0.17
Man	68	9	19	82	-1	91	90	0.9	50	79	-3	90	87	0.9	24	-0.38	-0.34	60	-8	0.8	9	4.2	-23	0	1	0	-0.10	-0.18
Man	68	125	20	107	4	92	96	1.2	50	106	-3	91	88	1.2	41	-0.32	-0.28	85	-9	1.0	11	3.9	-20	0	0	0	-0.05	-0.19
Man	50	155	21	86	-10	96	86	0.9	8	68	-15	93	78	0.7	5	-0.34	-0.22	18	-18	0.3	2	4.4	-32	1	1	1	-0.20	-0.26
Man	88	1	22	84	1	103	104	0.8	50	80	-5	103	99	0.8	17	-0.21	-0.23	65	-6	0.7	12	4.2	-18	0	0	0	-0.15	-0.12
Man	19	17	23	143	-3	81	78	1.8	42	114	-17	79	62	1.4	7	-0.28	-0.27	74	-19	1.3	5	2.9	-21	0	1	0	-0.10	-0.24
Man	59	78	24	123	0	104	104	1.2	50	94	-19	102	83	0.9	5	-0.30	-0.39	73	-20	0.8	5	1.9	-12	0	1	1	-0.10	-0.30
Man	61	52	25	104	1	84	86	1.2	50	99	-4	83	79	1.2	24	-0.27	-0.33	85	-9	1.2	10	2.8	-17	0	1	0	-0.10	-0.19
Man	52	44	26	50	-3	100	97	0.5	19	45	-5	98	93	0.5	9	-0.24	-0.14	42	-8	0.4	7	1.4	-10	0	1	0	-0.05	-0.08
Man	85	18	27	102	-1	75	74	1.4	50	84	-14	74	60	1.1	6	-0.25	-0.30	32	-16	0.8	4	7.8	-36	0	1	1	-0.15	-0.24
Man	73	130	28	69	-3	98	94	0.7	20	61	-7	96	89	0.6	9	-0.15	-0.17	52	-7	0.6	8	1.6	-7	0	1	0	-0.05	-0.11
Man	85	70	29	60	0	92	92	0.7	0	59	-1	92	90	0.6	46	-0.32	-0.63	41	-7	0.6	6	3.5	-26	0	1	0	-0.15	-0.16
Man	96	90	30	63	-2	90	88	0.7	28	58	-5	89	84	0.6	11	-0.19	-0.14	52	-6	0.6	10	3.0	-15	0	1	0	-0.15	-0.08
Man	56	71	31	107	-2	78	76	1.4	49	93	-8	76	69	1.2	12	-0.18	-0.23	71	-10	1.1	8	3.1	-15	0	1	0	-0.10	-0.16
Man	85	217	32	48	-1	96	95	0.5	40	44	-5	95	90	0.5	8	-0.35	-0.32	33	-10	0.4	4	2.1	-16	0	1	1	-0.10	-0.22
Man	81	176	33	81	-2	98	95	0.8	34	74	-8	95	88	0.8	10	-0.37	-0.21	67	-8	0.8	9	3.1	-23	0	1	0	-0.10	-0.14
Man	87	174	34	71	-3	80	77	0.9	26	68	-5	79	74	0.9	13	-0.16	-0.15	50	-13	0.7	7	3.9	-14	0	1	0	-0.05	-0.11
Man	68	170	35	109	1	112	114	1.0	50	107	-3	111	108	1.0	32	-0.23	-0.32	86	-10	0.9	10	3.3	-16	0	1	0	-0.05	-0.20

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						ΔT & V		Warnings			Severity	
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	96	76	36	206	-2	78	77	2.6	50	182	-12	75	63	2.4	15	-0.21	-0.22	130	-15	2.3	11	5.5	-25	0	0	0	-0.10	-0.18
Man	85	41	37	86	-5	94	88	0.9	16	76	-10	92	82	0.8	8	-0.28	-0.39	39	-12	0.6	5	13.3	-62	0	1	1	-0.15	-0.29
Man	64	4	38	67	-1	95	94	0.7	50	60	-7	94	86	0.6	8	-0.38	-0.34	36	-9	0.5	4	5.8	-35	0	1	1	-0.20	-0.21
Man	85	76	39	86	-7	91	84	0.9	13	74	-12	90	78	0.8	6	-0.40	-0.26	52	-14	0.7	5	3.5	-19	0	1	1	-0.10	-0.19
Man	63	189	40	196	-4	86	83	2.3	50	179	-10	85	75	2.1	18	-0.23	-0.26	37	-16	1.6	4	12.7	-65	0	1	0	-0.15	-0.23
Man	63	278	41	79	2	79	81	1.0	50	72	-6	78	72	0.9	12	-0.19	-0.21	68	-6	0.9	12	1.7	-7	0	0	0	-0.05	-0.13
Man	56	71	42	81	-3	92	89	0.9	29	76	-5	91	86	0.8	15	-0.25	-0.27	54	-10	0.7	6	4.2	-21	0	1	1	-0.10	-0.19
Man	85	226	43	47	-2	87	85	0.5	24	43	-5	86	81	0.5	9	-0.14	-0.18	38	-5	0.5	8	1.5	-6	0	1	0	-0.05	-0.09
Man	52	15	44	69	0	106	106	0.7	50	66	-4	105	101	0.6	18	-0.26	-0.15	64	-4	0.6	17	3.0	-14	0	0	0	-0.05	-0.09
Man	85	272	45	122	2	106	108	1.2	50	119	-4	106	101	1.1	28	-0.17	-0.24	99	-9	1.1	13	3.9	-13	0	0	0	-0.05	-0.17
Man	85	144	46	98	-6	104	99	0.9	18	91	-10	103	94	0.9	9	-0.22	-0.24	67	-12	0.7	7	3.0	-14	0	1	1	-0.10	-0.16
Man	85	118	47	51	2	89	90	0.6	50	51	0	89	88	0.6	50	-0.21	-0.21	46	-3	0.5	16	2.6	-10	0	0	0	-0.05	-0.10
Man	52	53	48	48	-4	102	98	0.5	11	40	-8	103	94	0.4	5	-0.37	-0.19	35	-9	0.4	4	1.5	-14	0	1	1	-0.10	-0.14
Man	52	56	49	48	-9	100	91	0.5	5	41	-10	100	89	0.4	4	-0.20	-0.20	31	-12	0.3	3	1.4	-7	0	1	1	-0.10	-0.10
Man	88	207	50	85	1	77	78	1.1	50	82	-3	77	74	1.1	26	-0.23	-0.24	69	-8	1.0	9	3.6	-12	0	1	0	-0.05	-0.15
Man	75	4	51	136	1	75	76	1.8	50	122	-11	75	65	1.6	11	-0.26	-0.26	102	-13	1.6	9	4.2	-18	0	1	0	-0.05	-0.18
Man	77	72	52	82	-6	113	107	0.7	13	78	-9	113	104	0.7	9	-0.20	-0.26	58	-13	0.6	6	2.6	-11	0	1	1	-0.10	-0.06
Man	81	92	53	72	1	85	86	0.8	50	70	-3	85	82	0.8	25	-0.24	-0.24	61	-5	0.8	13	3.8	-17	0	0	0	-0.05	-0.14
Man	85	70	54	73	-3	86	83	0.8	24	67	-7	85	78	0.8	10	-0.30	-0.25	47	-9	0.7	6	4.3	-24	0	1	0	-0.15	-0.16
Man	89	113	55	45	-1	77	76	0.6	50	45	0	78	77	0.6	50	-0.23	-0.20	34	-4	0.5	10	6.7	-25	0	0	0	-0.10	-0.01
Man	52	8	56	87	1	78	79	1.1	50	85	-3	77	74	1.1	32	-0.24	-0.19	78	-5	1.1	15	2.5	-12	0	0	0	-0.05	-0.11
Man	88	1	57	90	-1	104	103	0.9	50	87	-5	104	99	0.8	18	-0.23	-0.18	77	-6	0.8	14	2.8	-14	0	0	0	-0.10	-0.10
Man	44	91	58	405	-18	88	70	4.6	23	279	-38	86	48	3.3	7	-0.26	-0.33	161	-45	2.3	4	2.9	-16	0	1	1	-0.05	-0.43
Man	52	47	59	68	1	95	96	0.7	50	64	-4	95	90	0.7	16	-0.16	-0.17	58	-5	0.7	13	2.2	-10	0	0	0	-0.05	-0.09
Man	49	48	60	54	4	98	102	0.6	50	54	-1	98	97	0.6	50	-0.22	-0.20	41	-2	0.4	32	1.8	-10	0	0	0	-0.05	-0.10
Man	85	37	61	84	-4	100	97	0.8	21	76	-8	100	92	0.8	9	-0.17	-0.15	61	-10	0.7	7	2.1	-9	0	1	1	-0.05	-0.12
Man	96	2	62	94	-1	83	82	1.1	50	91	-3	81	78	1.1	28	-0.14	-0.15	82	-5	1.1	19	2.3	-8	0	0	0	-0.10	-0.10
Man	76	25	63	29	-1	95	94	0.3	20	28	-2	95	93	0.3	15	-0.13	-0.15	25	-3	0.3	10	1.7	-7	0	1	1	-0.05	-0.08
Man	61	52	64	147	-2	77	75	1.9	50	127	-14	77	63	1.6	9	-0.23	-0.25	90	-16	1.5	7	2.8	-18	0	1	0	-0.10	-0.22
Man	85	130	65	45	0	76	76	0.6	50	38	-7	74	67	0.5	5	-0.18	-0.22	29	-8	0.4	5	2.0	-7	0	1	1	-0.05	-0.16
Man	3	28	66	173	-1	78	77	2.2	50	162	-7	80	73	2.0	23	-0.25	-0.30	50	-22	1.0	4	7.0	-31	0	1	1	-0.10	-0.29
Man	29	22	67	171	-2	107	105	1.6	50	163	-5	106	101	1.5	31	-0.18	-0.22	141	-9	1.5	16	2.6	-10	0	0	0	-0.05	-0.15
Man	73	83	68	34	0	75	75	0.5	0	32	-3	73	71	0.4	13	-0.20	-0.18	29	-4	0.4	9	2.1	-10	0	1	0	-0.10	-0.10
Man	73	121	69	32	1	79	80	0.4	50	31	-1	78	78	0.4	34	-0.20	-0.27	22	-2	0.3	16	4.8	-22	0	0	0	-0.15	-0.08
Man	80	3	70	39	-2	77	75	0.5	24	40	-2	77	75	0.5	26	-0.20	-0.20	30	-5	0.4	6	7.1	-26	0	1	0	-0.10	-0.14

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						ΔT & V		Warnings			Severity	
Ctrl	Drv	Trip	Ev	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	Ydot, g	YpDot, g	R, ft	Rdot, ft/s	Hm, s	Ttc	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	90	142	71	81	-5	76	72	1.1	18	80	-5	75	70	1.1	15	-0.24	-0.18	60	-9	0.9	8	5.6	-23	0	1	0	-0.05	-0.13
Man	76	120	72	82	-4	98	94	0.8	21	76	-9	98	89	0.8	9	-0.23	-0.22	47	-11	0.6	5	3.1	-15	0	1	1	-0.05	-0.17
Man	68	126	73	118	-2	88	86	1.3	50	112	-8	87	80	1.3	15	-0.29	-0.24	91	-10	1.2	10	5.8	-25	0	1	0	-0.10	-0.15
Man	68	125	74	77	-1	90	89	0.9	50	76	-2	89	87	0.9	36	-0.18	-0.17	69	-5	0.8	15	3.5	-12	0	0	0	-0.05	-0.10
Man	7	6	75	53	1	81	82	0.6	50	51	-1	81	80	0.6	50	-0.25	-0.31	19	-7	0.4	4	8.7	-41	0	1	1	-0.15	-0.21
Man	77	145	76	99	-1	115	114	0.9	50	99	-2	114	113	0.9	50	-0.26	-0.16	95	-3	0.8	32	3.5	-18	0	0	0	-0.05	-0.09
Man	89	259	77	130	-4	86	83	1.5	36	120	-9	84	75	1.4	13	-0.16	-0.29	87	-13	1.3	9	4.9	-19	0	1	0	-0.10	-0.21
Man	68	147	78	63	-1	102	101	0.6	50	62	-2	102	100	0.6	33	-0.20	-0.18	57	-4	0.6	14	2.4	-10	0	0	0	-0.05	-0.08
Man	61	52	79	89	-3	75	72	1.2	28	78	-10	73	63	1.1	8	-0.27	-0.25	58	-11	1.0	6	5.1	-21	0	1	0	-0.10	-0.18
Man	89	271	80	33	1	82	83	0.4	50	31	-3	81	79	0.4	11	-0.15	-0.15	29	-13	0.4	10	3.0	-10	0	1	0	-0.05	-0.09
Man	68	62	81	106	-2	81	80	1.3	50	98	-6	80	73	1.2	15	-0.18	-0.16	87	-8	1.2	12	2.2	-8	0	0	0	-0.05	-0.12
Man	61	25	82	63	-4	78	73	0.8	14	57	-7	77	70	0.7	8	-0.20	-0.24	44	-9	0.6	5	1.8	-9	0	1	1	-0.05	-0.15
Man	66	210	83	235	-3	78	75	3.0	50	191	-19	76	57	2.5	10	-0.17	-0.29	159	-19	2.3	9	2.0	-8	0	1	0	-0.05	-0.20
Man	68	74	84	80	3	86	89	0.9	50	78	-4	86	82	0.9	19	-0.33	-0.34	46	-10	0.8	7	5.6	-34	0	1	0	-0.15	-0.22
Man	34	82	85	90	2	101	103	0.9	50	88	-3	100	97	0.9	25	-0.36	-0.40	72	-11	0.8	7	2.9	-22	0	1	0	-0.05	-0.25
Man	10	36	86	79	2	75	77	1.1	50	74	-2	73	71	1.0	30	-0.18	-0.23	68	-5	1.0	15	2.3	-11	0	0	0	-0.05	-0.14
Man	29	47	87	33	-1	91	90	0.4	33	32	-1	90	89	0.4	23	-0.17	-0.15	31	-4	0.3	9	1.4	-7	0	1	0	-0.05	-0.06
Man	1	98	88	86	1	79	80	1.1	50	84	0	79	79	1.1	50	-0.20	-0.29	64	-8	1.0	9	3.6	-14	0	1	0	-0.15	-0.19
Man	85	174	89	82	-3	84	81	1.0	25	79	-5	84	79	0.9	16	-0.27	-0.31	13	-8	0.8	2	15.0	-72	1	1	0	-0.15	-0.26
Man	87	177	90	15	-1	100	99	0.2	12	13	-2	100	98	0.1	6	-0.13	-0.14	10	-3	0.1	3	1.9	-7	1	1	1	-0.05	-0.07
Man	73	110	91	77	-2	89	88	0.9	45	74	-5	89	84	0.8	15	-0.26	-0.30	49	-11	0.7	6	3.2	-15	0	1	1	-0.10	-0.18
Man	85	223	92	97	-11	100	90	1.0	9	89	-15	100	85	0.9	6	-0.42	-0.29	36	-21	0.5	3	3.9	-26	1	1	1	-0.15	-0.29
Man	14	16	93	64	-6	84	79	0.8	11	62	-7	84	77	0.7	9	-0.26	-0.26	39	-13	0.6	4	2.7	-15	0	1	1	-0.10	-0.17
Man	89	51	94	109	1	74	75	1.5	50	98	-11	75	64	1.3	9	-0.29	-0.29	17	-13	1.0	3	11.4	-65	1	1	0	-0.20	-0.26
Man	69	1	95	69	0	78	78	0.9	0	68	-1	78	77	0.9	50	-0.23	-0.30	53	-6	0.8	12	5.1	-20	0	0	0	-0.10	-0.15
Man	77	18	96	109	-5	86	81	1.3	23	102	-7	85	78	1.2	14	-0.18	-0.20	74	-12	1.0	7	2.7	-10	0	1	0	-0.05	-0.15
Man	85	35	97	53	3	104	107	0.5	50	51	-3	103	100	0.5	17	-0.32	-0.44	41	-8	0.4	6	1.9	-13	0	1	1	-0.10	-0.25
Man	44	65	98	83	6	74	80	1.1	50	83	-2	75	73	1.1	45	-0.29	-0.34	51	-8	0.8	9	5.8	-40	0	1	0	-0.15	-0.20
Man	85	77	99	48	0	84	84	0.6	50	46	-3	83	80	0.6	15	-0.34	-0.31	40	-5	0.5	8	2.2	-15	0	1	0	-0.10	-0.15
Man	85	35	100	43	-2	102	99	0.4	18	42	-4	101	97	0.4	11	-0.23	-0.22	35	-5	0.4	7	3.3	-15	0	1	1	-0.10	-0.13
Man	52	47	101	71	0	77	77	0.9	50	70	-1	77	76	0.9	50	-0.18	-0.16	66	-3	0.9	24	2.9	-10	0	0	0	-0.10	-0.08
Man	50	73	102	97	-2	81	79	1.2	44	96	-3	81	79	1.2	34	-0.26	-0.25	67	-9	1.1	9	6.0	-33	0	1	0	-0.15	-0.17
Man	8	79	103	93	-8	89	81	1.0	11	90	-9	89	81	1.0	10	-0.33	-0.25	74	-10	0.9	8	4.6	-25	0	1	0	-0.10	-0.12
Man	6	10	104	172	-1	76	76	2.3	50	144	-12	73	61	2.0	12	-0.13	-0.24	108	-15	1.7	8	2.8	-10	0	1	0	-0.15	-0.20
Man	34	82	105	60	1	98	98	0.6	50	60	-1	97	96	0.6	50	-0.40	-0.35	50	-7	0.5	8	2.9	-22	0	1	0	-0.10	-0.19

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						ΔT & V		Warnings			Severity	
Ctrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	4	69	106	67	0	85	85	0.8	50	60	-4	84	80	0.7	14	-0.23	-0.25	52	-6	0.7	8	2.1	-11	0	1	0	-0.05	-0.13
Man	96	100	107	90	-2	89	87	1.0	43	88	-3	89	86	1.0	28	-0.29	-0.41	55	-13	0.9	5	5.4	-29	0	1	1	-0.15	-0.29
Man	87	69	108	73	0	76	76	1.0	50	71	-4	76	73	0.9	19	-0.35	-0.35	60	-7	0.9	8	3.3	-22	0	1	0	-0.10	-0.17
Man	78	195	109	98	-3	91	87	1.1	28	93	-7	91	84	1.0	13	-0.31	-0.32	71	-12	0.9	7	3.9	-25	0	1	0	-0.10	-0.20
Man	30	15	110	127	-6	86	81	1.5	22	113	-11	85	74	1.3	11	-0.22	-0.17	91	-12	1.2	9	2.7	-11	0	1	0	-0.05	-0.13
Man	68	125	111	58	-4	97	93	0.6	14	56	-5	96	91	0.6	12	-0.46	-0.37	34	-10	0.5	4	4.2	-35	0	1	1	-0.20	-0.24
Man	85	39	112	61	-9	74	65	0.8	7	52	-13	74	61	0.7	4	-0.30	-0.26	34	-14	0.6	3	2.7	-14	0	1	1	-0.05	-0.20
Man	41	47	113	15	-2	87	86	0.2	9	16	-2	89	87	0.2	9	-0.27	-0.23	14	-2	0.2	8	2.6	-12	0	1	1	-0.05	-0.09
Man	4	44	114	39	-3	99	96	0.4	14	38	-3	99	96	0.4	13	-0.21	-0.23	31	-5	0.3	6	2.1	-10	0	1	1	-0.10	-0.13
Man	89	158	115	101	-6	101	95	1.0	16	94	-10	101	91	0.9	10	-0.20	-0.21	61	-13	0.7	6	3.1	-13	0	1	1	-0.10	-0.15
Man	66	157	116	102	-9	95	87	1.1	12	90	-16	95	79	1.0	6	-0.54	-0.42	52	-22	0.7	3	3.4	-34	1	1	1	-0.15	-0.37
Man	87	108	117	99	-3	88	85	1.1	30	94	-6	86	80	1.1	16	-0.24	-0.40	69	-9	1.0	9	4.6	-20	0	1	0	-0.05	-0.18
Man	49	3	118	85	-2	100	98	0.9	49	79	-7	99	92	0.8	11	-0.19	-0.26	73	-8	0.8	9	1.7	-7	0	1	0	-0.05	-0.13
Man	55	66	119	78	2	90	92	0.9	50	77	-2	90	88	0.9	47	-0.14	-0.21	68	-4	0.8	20	2.1	-7	0	0	0	-0.05	-0.11
Man	85	34	120	68	-7	98	90	0.7	9	66	-8	98	90	0.7	8	-0.26	-0.20	42	-14	0.5	6	4.7	-24	0	1	1	-0.10	-0.12
Man	52	47	121	64	-1	89	88	0.7	50	60	-6	89	83	0.7	10	-0.40	-0.45	49	-10	0.6	5	2.4	-19	0	1	1	-0.15	-0.24
Man	85	1	122	32	-1	74	73	0.4	32	29	-5	73	69	0.4	6	-0.18	-0.19	24	-5	0.4	5	1.7	-7	0	1	1	-0.05	-0.12
Man	9	63	123	216	-1	84	83	2.6	50	188	-11	83	72	2.3	17	-0.20	-0.26	168	-13	2.3	14	2.5	-10	0	0	0	-0.05	-0.16
Man	85	18	124	41	2	97	99	0.4	50	39	-1	96	95	0.4	31	-0.20	-0.24	34	-3	0.4	11	1.9	-9	0	0	0	-0.05	-0.11
Man	88	176	125	145	-1	81	80	1.8	50	131	-11	81	71	1.6	12	-0.27	-0.31	68	-13	1.5	6	6.4	-42	0	1	0	-0.15	-0.24
Man	1	37	126	92	-1	88	87	1.0	50	90	-2	88	86	1.0	43	-0.19	-0.23	71	-6	1.0	12	3.9	-16	0	0	0	-0.05	-0.15
Man	85	144	127	54	0	108	107	0.5	50	52	-3	107	104	0.5	16	-0.21	-0.17	50	-4	0.5	14	2.5	-9	0	0	0	-0.05	-0.07
Man	93	89	128	153	-6	77	70	2.0	24	131	-16	75	60	1.7	8	-0.46	-0.38	27	-24	0.8	1	5.2	-43	1	1	1	-0.20	-0.45
Man	68	53	129	53	0	74	74	0.7	50	52	-1	74	73	0.7	50	-0.17	-0.25	46	-5	0.6	10	2.9	-11	0	1	0	-0.05	-0.13
Man	80	3	130	85	-2	103	100	0.8	37	82	-6	102	96	0.8	14	-0.26	-0.27	28	-11	0.5	4	10.4	-48	0	1	1	-0.15	-0.21
Man	85	70	131	54	-2	86	85	0.6	30	52	-4	86	82	0.6	12	-0.26	-0.21	41	-6	0.5	7	3.0	-12	0	1	0	-0.05	-0.10
Man	63	290	132	92	-11	82	71	1.1	9	84	-13	81	68	1.0	6	-0.19	-0.23	40	-17	0.7	4	5.6	-24	0	1	1	-0.10	-0.21
Man	87	140	133	45	-5	98	93	0.5	10	45	-4	98	93	0.5	10	-0.15	-0.16	36	-11	0.4	6	2.3	-9	0	1	1	-0.05	-0.09
Man	85	37	134	245	-12	96	84	2.5	21	212	-21	94	73	2.3	10	-0.40	-0.32	95	-26	2.0	7	6.6	-52	0	1	0	-0.20	-0.27
Man	85	307	135	43	-1	81	80	0.5	50	39	-6	81	75	0.5	7	-0.20	-0.23	35	-6	0.5	6	1.5	-8	0	1	1	-0.05	-0.11
Man	52	53	136	78	-3	95	92	0.8	26	70	-7	94	87	0.7	10	-0.19	-0.16	63	-8	0.7	9	1.3	-6	0	1	0	-0.05	-0.10
Man	73	18	137	149	-7	77	70	1.9	21	128	-15	75	60	1.7	8	-0.26	-0.23	108	-16	1.6	7	1.5	-9	0	1	0	-0.05	-0.17
Man	56	113	138	27	-7	94	86	0.3	4	27	-7	94	86	0.3	4	-0.15	-0.14	17	-7	0.2	3	2.8	-10	0	1	1	-0.10	-0.11
Man	88	177	139	68	-2	100	98	0.7	32	64	-7	100	93	0.6	10	-0.53	-0.58	54	-10	0.6	5	2.3	-29	0	1	1	-0.20	-0.27
Man	84	27	140	89	-3	75	72	1.2	28	84	-5	75	70	1.1	19	-0.18	-0.24	75	-7	1.1	12	3.0	-11	0	0	0	-0.05	-0.11

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						Δ T & V		Warnings			Severity	
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Hm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	49	16	141	61	-2	90	88	0.7	26	63	-3	91	88	0.7	24	-0.20	-0.14	56	-4	0.7	16	2.9	-9	0	0	0	-0.05	-0.07
Man	61	42	142	138	3	78	80	1.8	50	137	-2	76	74	1.8	50	-0.20	-0.24	5	-14	1.6	2	21.8	-76	1	1	0	-0.15	-0.24
Man	55	79	143	84	-3	78	75	1.1	27	77	-7	77	70	1.0	11	-0.21	-0.21	66	-9	1.0	8	2.0	-10	0	1	0	-0.10	-0.13
Man	63	78	144	98	-2	78	76	1.2	45	95	-3	78	74	1.2	29	-0.17	-0.19	57	-9	1.0	7	6.3	-21	0	1	0	-0.10	-0.16
Man	12	36	145	38	0	80	80	0.5	50	37	-1	79	78	0.5	50	-0.15	-0.15	36	-1	0.5	28	2.2	-8	0	0	0	-0.05	-0.09
Man	85	35	146	81	-4	99	95	0.8	21	74	-8	98	90	0.8	9	-0.15	-0.21	58	-10	0.6	6	2.9	-10	0	1	1	-0.05	-0.14
Man	1	47	147	240	-1	89	88	2.7	50	208	-13	89	75	2.3	16	-0.22	-0.25	161	-15	2.3	12	4.2	-21	0	0	0	-0.10	-0.17
Man	96	2	148	73	-2	74	72	1.0	40	69	-5	75	70	0.9	14	-0.26	-0.30	59	-8	0.9	8	2.4	-13	0	1	0	-0.05	-0.15
Man	12	1	149	83	-4	80	76	1.0	23	79	-5	80	75	1.0	15	-0.16	-0.14	72	-6	1.0	13	2.6	-12	0	0	0	-0.05	-0.08
Man	14	17	150	25	-1	75	75	0.3	40	24	-2	75	73	0.3	16	-0.19	-0.26	18	-5	0.3	4	1.3	-7	0	1	1	-0.10	-0.16
Man	73	181	151	32	0	95	95	0.3	50	32	0	95	94	0.3	50	-0.14	-0.18	27	-3	0.3	10	3.0	-10	0	0	0	-0.05	-0.11
Man	4	44	152	26	-3	90	87	0.3	8	27	-3	91	88	0.3	9	-0.40	-0.42	19	-5	0.2	4	2.6	-20	0	1	1	-0.15	-0.21
Man	88	161	153	51	-3	95	92	0.5	16	51	-3	95	92	0.5	16	-0.45	-0.36	41	-5	0.5	8	3.6	-27	0	1	0	-0.15	-0.18
Man	73	181	154	37	-2	78	77	0.5	23	37	-1	78	76	0.5	27	-0.15	-0.17	31	-3	0.4	10	4.4	-15	0	0	0	-0.10	-0.08
Man	21	1	155	75	1	82	84	0.9	50	74	-2	82	80	0.9	43	-0.24	-0.38	54	-8	0.8	9	3.6	-19	0	1	0	-0.10	-0.20
Man	85	136	156	56	-4	87	84	0.6	15	56	-4	87	84	0.6	16	-0.31	-0.33	46	-8	0.6	6	2.5	-14	0	1	0	-0.10	-0.17
Man	59	66	157	33	-3	76	73	0.4	11	33	-3	76	73	0.4	11	-0.49	-0.53	15	-8	0.4	3	3.9	-38	1	1	1	-0.30	-0.30
Man	30	20	158	115	-2	84	81	1.4	50	111	-4	84	80	1.3	29	-0.16	-0.20	97	-8	1.3	14	2.6	-10	0	0	0	-0.05	-0.11
Man	89	212	159	147	-7	107	100	1.4	21	138	-10	106	96	1.3	14	-0.48	-0.17	130	-10	1.3	13	2.3	-23	0	0	0	-0.05	-0.09
Man	52	55	160	51	-4	77	72	0.7	11	50	-5	77	72	0.6	10	-0.29	-0.29	36	-8	0.6	5	3.7	-23	0	1	1	-0.10	-0.17
Man	59	67	161	86	-2	81	79	1.1	35	85	-3	81	78	1.0	29	-0.17	-0.32	42	-13	0.8	5	8.9	-35	0	1	1	-0.15	-0.10
Man	49	48	162	92	-3	91	88	1.0	34	90	-4	91	87	1.0	23	-0.19	-0.16	74	-6	0.9	13	5.4	-23	0	0	0	-0.10	-0.10
Man	61	2	163	91	-7	77	70	1.2	13	85	-9	77	68	1.1	10	-0.20	-0.30	61	-13	0.9	6	2.6	-14	0	1	0	-0.05	-0.19
Man	4	90	164	46	0	80	80	0.6	50	43	-2	79	77	0.5	25	-0.28	-0.42	33	-6	0.5	6	2.6	-16	0	1	1	-0.15	-0.22
Man	50	13	165	85	-7	75	68	1.1	13	79	-9	75	66	1.1	9	-0.22	-0.32	34	-16	0.7	5	6.0	-26	0	1	1	-0.15	-0.20
Man	4	103	166	113	-7	96	89	1.2	16	111	-8	96	88	1.2	14	-0.33	-0.38	42	-11	0.8	4	8.7	-48	0	1	0	-0.20	-0.28
Man	88	1	167	107	-1	111	109	1.0	50	104	-5	111	106	0.9	22	-0.25	-0.32	82	-9	0.9	10	4.3	-24	0	1	0	-0.10	-0.19
Man	56	91	168	102	-3	86	83	1.2	33	100	-4	86	82	1.2	26	-0.15	-0.20	84	-7	1.1	12	3.1	-10	0	0	0	-0.10	-0.12
Man	68	125	169	117	-4	109	105	1.1	33	117	-4	109	105	1.1	30	-0.21	-0.24	88	-9	1.0	12	7.0	-32	0	0	0	-0.10	-0.15
Man	88	1	170	109	-5	87	82	1.3	22	106	-8	87	79	1.2	14	-0.44	-0.75	56	-17	1.1	4	6.0	-48	0	1	1	-0.20	-0.35
Man	1	111	171	44	-1	80	79	0.5	40	44	-1	80	79	0.5	40	-0.20	-0.20	34	-3	0.5	15	5.4	-27	0	0	0	-0.15	-0.15
Man	85	1	172	46	-1	83	82	0.6	39	46	-1	83	82	0.6	39	-0.24	-0.27	35	-5	0.5	7	3.4	-18	0	1	0	-0.05	-0.16
Man	59	58	173	73	-2	100	98	0.7	35	72	-5	99	94	0.7	15	-0.56	-0.46	48	-10	0.6	5	3.5	-35	0	1	1	-0.20	-0.28
Man	85	239	174	145	-4	102	98	1.4	41	133	-14	103	89	1.3	10	-0.25	-0.35	83	-18	1.0	6	3.7	-21	0	1	1	-0.10	-0.24
Man	85	37	175	60	-1	90	89	0.7	50	58	-3	89	86	0.7	19	-0.18	-0.23	53	-10	0.6	7	2.2	-8	0	1	1	-0.05	-0.12

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						Δ T & V		Warnings			Severity	
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Hm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Hm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	52	63	176	80	-6	91	85	0.9	13	77	-6	90	84	0.9	12	-0.32	-0.22	70	-8	0.8	9	1.7	-12	0	1	0	-0.10	-0.10
Man	40	58	177	65	-1	84	82	0.8	50	64	-2	84	82	0.8	39	-0.14	-0.15	59	-3	0.8	22	2.5	-10	0	0	0	-0.05	-0.09
Man	88	207	178	60	0	108	108	0.6	50	59	-1	108	107	0.6	50	-0.19	-0.21	57	-3	0.5	19	1.7	-8	0	0	0	-0.05	-0.09
Man	59	4	179	102	-4	101	97	1.0	24	91	-12	100	88	0.9	8	-0.20	-0.32	80	-13	0.9	7	1.2	-6	0	1	1	-0.05	-0.19
Man	89	131	180	117	-3	87	85	1.3	46	114	-5	86	82	1.3	24	-0.22	-0.24	100	-7	1.3	15	3.6	-18	0	0	0	-0.05	-0.14
Man	85	136	181	44	-3	84	80	0.5	14	45	-3	84	82	0.5	17	-0.28	-0.16	41	-4	0.5	12	2.1	-12	0	0	0	-0.10	-0.06
Man	75	48	182	83	-4	81	77	1.0	19	81	-5	81	76	1.0	15	-0.15	-0.20	62	-9	0.9	7	2.5	-9	0	1	0	-0.05	-0.12
Man	59	68	183	58	-1	97	96	0.6	50	56	-5	97	92	0.6	11	-0.39	-0.47	43	-11	0.5	4	1.8	-12	0	1	1	-0.20	-0.23
Man	4	69	184	75	-1	98	97	0.8	50	74	-2	98	96	0.8	43	-0.21	-0.21	70	-3	0.7	23	3.1	-15	0	0	0	-0.05	-0.11
Man	4	44	185	42	-2	95	94	0.4	24	42	-2	95	94	0.4	24	-0.20	-0.22	37	-3	0.4	11	1.9	-10	0	0	0	-0.05	-0.11
Man	77	213	186	53	3	79	83	0.7	50	50	-4	78	74	0.6	12	-0.23	-0.31	45	-6	0.6	8	1.1	-7	0	1	0	-0.10	-0.18
Man	83	1	187	56	-4	82	79	0.7	16	54	-4	81	78	0.7	14	-0.29	-0.34	45	-7	0.6	7	2.3	-15	0	1	0	-0.05	-0.15
Man	85	224	188	158	-10	77	66	2.1	15	141	-15	76	61	1.9	10	-0.23	-0.28	85	-17	1.4	7	4.1	-15	0	1	0	-0.10	-0.18
Man	1	46	189	58	-3	92	89	0.6	19	57	-4	92	88	0.6	15	-0.17	-0.18	46	-5	0.6	10	2.7	-12	0	1	0	-0.20	-0.11
Man	4	49	190	62	-2	98	96	0.6	27	64	-2	98	97	0.6	39	-0.63	-0.80	34	-10	0.6	4	4.9	-57	0	1	1	-0.30	-0.41
Man	1	111	191	76	1	79	80	1.0	50	74	0	79	79	0.9	50	-0.21	-0.32	63	-5	0.9	12	2.5	-12	0	0	0	-0.05	-0.17
Man	56	109	192	58	-3	73	70	0.8	19	57	-3	73	70	0.8	17	-0.17	-0.18	33	-6	0.7	9	9.7	-34	0	1	0	-0.10	-0.13
Man	49	18	193	66	-1	89	88	0.7	50	67	0	89	89	0.7	50	-0.42	-0.48	54	-7	0.7	9	10.1	-54	0	1	0	-0.20	-0.21
Man	59	78	194	143	-1	102	101	1.4	50	143	-1	102	101	1.4	50	-0.23	-0.69	42	-16	0.4	8	7.2	-33	0	1	0	-0.10	-0.32
Man	68	170	195	145	-5	99	94	1.5	31	141	-6	98	91	1.5	22	-0.17	-0.20	126	-9	1.4	15	2.5	-10	0	0	0	-0.05	-0.12
Man	89	263	196	84	-1	84	83	1.0	50	83	-2	84	81	1.0	40	-0.22	-0.26	66	-6	1.0	11	11.0	-37	0	0	0	-0.10	-0.14
Man	89	142	197	176	-3	97	94	1.8	50	168	-8	95	87	1.8	21	-0.21	-0.26	142	-11	1.7	15	3.2	-17	0	0	0	-0.05	-0.15
Man	20	41	198	63	-2	82	80	0.8	27	61	-3	82	79	0.7	18	-0.35	-0.36	43	-7	0.7	6	3.9	-29	0	1	0	-0.15	-0.24
Man	34	81	199	57	-2	84	81	0.7	26	55	-3	84	80	0.7	16	-0.25	-0.32	44	-7	0.6	7	3.0	-13	0	1	0	-0.05	-0.15
Man	78	181	200	115	-1	84	83	1.4	50	115	-2	84	82	1.4	50	-0.15	-0.27	96	-9	1.3	12	3.8	-15	0	0	0	-0.05	-0.17
Man	57	47	201	167	1	79	80	2.1	50	163	-4	78	73	2.1	37	-0.22	-0.28	54	-18	2.0	4	11.8	-54	0	1	0	-0.15	-0.30
Man	77	253	202	77	-3	97	94	0.8	26	74	-4	96	92	0.8	19	-0.18	-0.11	69	-5	0.8	15	1.7	-7	0	0	0	-0.05	-0.06
Man	4	61	203	87	-6	94	88	0.9	14	84	-6	93	87	0.9	13	-0.17	-0.17	76	-7	0.9	12	1.8	-8	0	0	0	-0.05	-0.08
Man	4	105	204	92	-7	89	83	1.0	14	90	-7	89	82	1.0	13	-0.30	-0.19	80	-8	1.0	11	3.5	-20	0	0	0	-0.10	-0.02
Man	44	85	205	98	-3	75	72	1.3	35	91	-10	74	64	1.2	9	-0.36	-0.41	45	-16	1.0	4	3.4	-28	0	1	1	-0.15	-0.33
Man	89	142	206	89	-1	109	107	0.8	50	89	-1	109	107	0.8	50	-0.26	-0.17	87	-5	0.8	18	2.3	-14	0	0	0	-0.05	-0.06
Man	89	263	207	217	1	84	85	2.6	50	200	-14	82	68	2.4	14	-0.30	-0.39	169	-17	2.4	11	3.5	-19	0	1	0	-0.10	-0.27
Man	63	290	208	115	-2	81	79	1.4	50	113	-3	80	76	1.4	33	-0.26	-0.34	9	-11	1.3	2	15.6	-80	1	1	0	-0.20	-0.29
Man	8	29	209	113	-11	108	97	1.1	11	105	-11	107	96	1.0	10	-0.22	-0.19	95	-13	0.9	9	1.2	-7	0	1	0	-0.05	-0.08
Man	14	17	210	94	-1	86	84	1.1	50	88	-9	84	75	1.0	10	-0.36	-0.52	14	-15	0.6	2	14.8	-75	1	1	1	-0.25	-0.33

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						ACC Vehicle Brake On						Event Minimums						ΔT & ΔV		Warnings			Severity	
Cntrl	Drv	Trip	Ev #	R ft	Rdot ft/s	V ft/s	Vp ft/s	Hm s	Ttc s	R ft	Rdot ft/s	V ft/s	Vp ft/s	Hm s	Ttc s	Vdot g	VpDot g	R ft	Rdot ft/s	Hm s	Ttc s	ΔT s	ΔV ft/s	NHTSA	Ttc	Vc Dot	Const Ax g	Avoid Ax g
Man	7	15	211	125	-3	78	76	1.6	44	124	-3	78	75	1.6	37	-0.42	-0.41	28	-18	1.1	2	8.8	-71	1	1	0	-0.25	-0.45
Man	81	36	212	76	-2	73	71	1.0	38	74	-4	73	69	1.0	17	-0.27	-0.29	62	-13	1.0	7	6.6	-25	0	1	0	-0.10	-0.17
Man	4	69	213	72	-4	87	84	0.8	20	68	-5	86	82	0.8	14	-0.17	-0.20	62	-6	0.8	11	1.9	-8	0	0	0	-0.05	-0.09
Man	68	125	214	96	-2	100	99	1.0	50	96	-1	100	99	1.0	50	-0.18	-0.19	88	-5	0.9	19	3.6	-14	0	0	0	-0.05	-0.10
Man	52	17	215	49	-4	85	81	0.6	11	51	-4	86	82	0.6	13	-0.35	-0.30	45	-5	0.6	11	3.6	-22	0	1	0	-0.10	-0.12
Man	4	49	216	58	-1	85	84	0.7	40	58	-1	85	84	0.7	46	-0.23	-0.26	48	-5	0.6	11	3.5	-15	0	0	0	-0.10	-0.15
Man	63	290	217	152	0	83	83	1.8	0	148	-5	82	77	1.8	28	-0.31	-0.32	10	-16	1.5	3	16.4	-82	0	1	0	-0.20	-0.27
Man	77	1	218	108	-9	101	92	1.1	12	108	-9	101	92	1.1	12	-0.42	-0.32	68	-14	0.9	6	4.4	-35	0	1	1	-0.20	-0.23
Man	7	12	219	59	-2	85	83	0.7	29	59	-1	85	84	0.7	41	-0.18	-0.28	46	-7	0.6	7	2.8	-12	0	1	0	-0.05	-0.16
Man	81	36	220	84	1	78	78	1.1	50	78	-6	78	72	1.0	13	-0.20	-0.22	73	-7	1.0	11	1.7	-9	0	1	0	-0.05	-0.14
Man	12	62	221	114	-8	90	82	1.3	14	112	-8	90	82	1.2	14	-0.16	-0.16	91	-10	1.1	9	2.3	-9	0	0	0	-0.10	-0.06
Man	4	69	222	46	-2	92	90	0.5	23	46	-2	91	88	0.5	19	-0.23	-0.28	37	-6	0.4	6	1.7	-8	0	1	1	-0.05	-0.14
Man	1	46	223	52	-3	84	81	0.6	19	52	-3	84	82	0.6	21	-0.34	-0.34	46	-4	0.6	11	2.7	-21	0	0	0	-0.10	-0.19
Man	85	70	224	226	-15	104	89	2.2	15	190	-25	104	79	1.8	8	-0.23	-0.22	111	-26	1.4	6	4.2	-23	0	1	1	-0.10	-0.20
Man	29	4	225	245	-10	81	71	3.0	24	210	-17	78	61	2.7	12	-0.20	-0.24	115	-21	2.2	7	5.9	-26	0	1	0	-0.10	-0.22
Man	49	9	226	193	-4	102	98	1.9	48	188	-8	101	94	1.9	25	-0.29	-0.40	141	-18	1.7	8	3.1	-18	0	1	0	-0.05	-0.30
Man	89	171	227	45	-2	78	76	0.6	26	45	-2	78	76	0.6	27	-0.20	-0.25	40	-4	0.6	10	5.0	-18	0	0	0	-0.10	-0.12
Man	85	17	228	71	-1	111	111	0.6	50	72	-1	113	112	0.6	50	-0.34	-0.40	43	-10	0.5	5	6.1	-35	0	1	1	-0.15	-0.28
Man	1	98	229	52	-4	80	75	0.6	12	55	-4	81	77	0.7	13	-0.26	-0.27	40	-7	0.6	6	3.8	-20	0	1	0	-0.10	-0.17
Man	65	53	230	231	-14	87	73	2.6	17	192	-25	85	60	2.3	8	-0.42	-0.39	80	-29	2.0	5	5.0	-48	0	1	0	-0.20	-0.32
Man	4	76	231	68	-6	86	80	0.8	11	68	-6	86	80	0.8	11	-0.25	-0.24	60	-7	0.8	10	2.9	-16	0	1	0	-0.05	-0.11
Man	30	77	232	92	-3	86	84	1.1	32	91	-3	86	83	1.1	27	-0.14	-0.14	83	-5	1.0	19	2.0	-7	0	0	0	-0.05	-0.08
Man	85	51	233	219	-8	106	99	2.1	29	206	-15	106	91	2.0	14	-0.37	-0.40	40	-22	1.4	4	12.1	-78	0	1	0	-0.20	-0.36
Man	7	15	234	90	-3	75	72	1.2	26	90	-3	75	72	1.2	26	-0.39	-0.47	40	-15	0.9	3	9.2	-54	0	1	1	-0.20	-0.37
Man	94	11	235	95	-8	78	71	1.2	12	93	-9	78	69	1.2	11	-0.41	-0.37	12	-10	1.1	3	14.0	-78	0	1	0	-0.25	-0.28
Man	49	9	236	115	-5	103	97	1.1	21	115	-6	103	97	1.1	19	-0.21	-0.22	94	-8	1.1	12	3.4	-18	0	0	0	-0.05	-0.14
Man	85	96	237	54	-2	74	72	0.7	23	54	-3	74	71	0.7	20	-0.25	-0.15	51	-3	0.7	17	3.7	-20	0	0	0	-0.10	-0.05
Man	87	44	238	96	-2	95	93	1.0	50	96	-2	94	92	1.0	48	-0.19	-0.23	74	-4	1.0	22	14.6	-52	0	0	0	-0.15	-0.19
Man	4	103	239	68	-7	75	68	0.9	9	70	-7	76	69	0.9	9	-0.21	-0.12	52	-9	0.8	8	5.1	-23	0	1	0	-0.10	-0.09
Man	4	105	240	137	-5	100	94	1.4	25	136	-5	100	94	1.4	25	-0.17	-0.16	123	-7	1.3	19	3.4	-13	0	0	0	-0.05	-0.09
Man	68	164	241	79	0	77	77	1.0	50	79	0	78	78	1.0	50	-0.26	-0.25	16	-9	1.0	4	18.5	-73	0	1	0	-0.15	-0.23
Man	1	46	242	66	-1	86	85	0.8	50	66	0	86	85	0.8	50	-0.30	-0.29	62	-2	0.7	35	2.3	-14	0	0	0	-0.10	-0.13
Man	29	38	243	81	-4	81	77	1.0	18	82	-4	81	77	1.0	19	-0.19	-0.27	59	-9	0.9	7	5.4	-22	0	1	0	-0.10	-0.17
Man	49	52	244	107	-1	102	101	1.0	50	107	-1	102	100	1.0	50	-0.17	-0.13	105	-2	1.0	50	2.2	-9	0	0	0	-0.05	-0.05
Man	89	111	245	158	-7	89	83	1.8	24	158	-7	89	83	1.8	24	-0.23	-0.24	20	-10	1.7	4	19.5	-87	0	1	0	-0.15	-0.21

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						ΔT & V		Warnings			Severity	
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	79	197	246	69	-2	77	75	0.9	30	70	-3	78	75	0.9	25	-0.18	-0.16	63	-3	0.9	20	4.3	-16	0	0	0	-0.10	-0.10
Man	4	61	247	75	-3	83	80	0.9	25	73	-3	83	80	0.9	22	-0.26	-0.29	69	-5	0.9	15	1.9	-12	0	0	0	-0.05	-0.11
Man	96	37	248	71	-2	87	85	0.8	37	71	-2	88	86	0.8	37	-0.20	-0.27	66	-4	0.8	16	1.4	-8	0	0	0	-0.20	-0.11
Man	64	12	249	116	2	81	84	1.4	50	115	0	80	79	1.4	50	-0.35	-0.38	8	-14	1.3	2	13.1	-80	1	1	0	-0.25	-0.33
Man	1	111	250	55	-2	75	73	0.7	25	56	-2	75	73	0.7	24	-0.26	-0.26	35	-3	0.7	12	11.5	-46	0	0	0	-0.15	-0.19
Man	51	28	251	61	-12	83	71	0.7	5	62	-12	83	71	0.8	5	-0.26	-0.13	49	-12	0.7	5	1.9	-10	0	1	1	-0.05	-0.08
Man	68	147	252	131	-4	112	108	1.2	30	130	-5	112	107	1.2	27	-0.24	-0.22	118	-8	1.1	16	2.5	-10	0	0	0	-0.05	-0.10
Man	89	181	253	112	-2	81	79	1.4	50	110	-3	80	77	1.4	34	-0.15	-0.20	99	-6	1.4	18	3.7	-14	0	0	0	-0.05	-0.11
Man	87	93	254	252	-14	80	66	3.2	18	212	-23	78	56	2.7	9	-0.27	-0.27	71	-28	0.0	3	5.5	-37	0	1	0	-0.15	-0.35
Man	56	71	255	84	-11	100	89	0.8	8	89	-10	100	90	0.9	8	-0.17	-0.17	54	-11	0.5	7	5.0	-22	0	1	0	-0.10	-0.12
Man	88	206	256	86	-6	84	78	1.0	14	90	-5	85	80	1.1	18	-0.22	-0.20	78	-7	1.0	14	3.1	-13	0	0	0	-0.10	-0.11
Man	44	86	257	60	-3	73	70	0.8	17	61	-3	73	70	0.8	20	-0.18	-0.18	47	-6	0.8	9	3.4	-13	0	1	0	-0.05	-0.12
Man	85	82	258	132	-11	92	80	1.4	12	133	-12	92	80	1.4	11	-0.24	-0.19	94	-14	1.2	8	3.9	-18	0	1	0	-0.10	-0.13
Man	89	181	259	120	-2	80	78	1.5	50	119	-2	80	78	1.5	50	-0.21	-0.19	105	-4	1.5	26	6.0	-30	0	0	0	-0.10	-0.14
Man	8	32	260	77	-4	75	72	1.0	20	76	-4	75	71	1.0	18	-0.23	-0.20	73	-4	1.0	17	1.4	-9	0	0	0	-0.05	-0.08
Man	4	61	261	134	-3	78	76	1.7	49	129	-5	78	73	1.6	25	-0.25	-0.41	83	-16	1.4	6	3.4	-21	0	1	0	-0.10	-0.30
Man	8	41	262	87	-2	78	76	1.1	40	86	-2	78	75	1.1	35	-0.16	-0.16	83	-13	1.1	18	2.6	-10	0	0	0	-0.10	-0.08
Man	4	61	263	111	-6	82	76	1.4	18	109	-6	81	75	1.3	18	-0.26	-0.22	103	-7	1.3	16	2.5	-17	0	0	0	-0.05	-0.09
Man	73	79	264	67	-5	73	68	0.9	12	70	-4	74	70	0.9	18	-0.44	-0.42	14	-13	0.7	2	9.4	-74	1	1	1	-0.25	-0.34
Man	1	37	265	177	-7	78	71	2.3	25	168	-9	78	68	2.2	18	-0.17	-0.26	129	-15	2.0	9	3.2	-13	0	1	0	-0.05	-0.19
Man	5	63	266	157	-6	77	70	2.0	24	149	-9	77	68	1.9	17	-0.30	-0.44	39	-18	1.7	5	10.3	-56	0	1	0	-0.20	-0.31
Man	75	75	267	119	-13	86	73	1.4	9	116	-13	86	72	1.4	9	-0.19	-0.17	93	-14	1.2	8	2.2	-11	0	1	0	-0.05	-0.09
Man	4	76	268	152	-9	85	76	1.8	17	153	-8	85	77	1.8	18	-0.25	-0.26	9	-15	1.3	3	19.8	-85	0	1	0	-0.15	-0.29
Man	84	17	269	138	-3	75	72	1.9	45	136	-4	75	71	1.8	36	-0.17	-0.17	126	-6	1.8	24	2.9	-11	0	0	0	-0.05	-0.09
Man	56	88	270	94	-1	83	82	1.1	50	95	-1	83	82	1.1	50	-0.33	-0.37	8	-12	1.1	1	12.3	-83	1	1	0	-0.25	-0.42
Man	73	56	271	135	-12	89	77	1.5	11	141	-13	89	77	1.6	11	-0.17	-0.19	67	-14	1.1	6	7.2	-27	0	1	0	-0.10	-0.17
Man	32	18	272	102	-15	78	63	1.3	7	100	-15	78	63	1.3	7	-0.36	-0.42	45	-21	0.9	2	3.1	-25	1	1	1	-0.05	-0.39
Man	89	275	273	99	1	85	86	1.2	50	97	-2	84	82	1.2	43	-0.23	-0.23	94	-4	1.1	27	2.5	-10	0	0	0	-0.05	-0.12
Man	68	59	274	134	-3	80	77	1.7	43	135	-3	80	77	1.7	46	-0.31	-0.44	70	-17	1.3	6	8.2	-32	0	1	0	-0.10	-0.33
Man	9	26	275	117	-2	77	75	1.5	49	117	-2	77	75	1.5	50	-0.15	-0.11	115	-3	1.5	45	2.5	-9	0	0	0	-0.05	-0.06
Man	5	64	276	131	-3	84	81	1.6	39	131	-3	84	81	1.6	39	-0.21	-0.22	107	-8	1.5	14	3.6	-17	0	0	0	-0.10	-0.16
Man	76	118	277	131	-2	75	73	1.8	50	128	-5	75	70	1.7	25	-0.17	-0.20	113	-7	1.7	17	4.1	-13	0	0	0	-0.05	-0.10
Man	68	125	278	161	-3	98	95	1.7	50	160	-4	98	94	1.6	40	-0.18	-0.24	145	-7	1.6	21	5.3	-21	0	0	0	-0.05	-0.13
Man	88	206	279	130	-5	89	84	1.4	24	129	-6	89	83	1.4	21	-0.41	-0.31	87	-15	1.3	6	4.9	-37	0	1	0	-0.15	-0.26
Man	9	81	280	136	-9	84	75	1.6	15	137	-9	84	76	1.6	16	-0.20	-0.23	77	-11	1.5	10	16.6	-67	0	1	0	-0.15	-0.16

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						ΔT & V		Warnings			Severity	
Cntrl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHTSA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Man	7	68	281	144	-12	83	71	1.7	12	141	-12	83	71	1.7	12	-0.19	-0.25	81	-16	1.3	6	4.4	-20	0	1	0	-0.10	-0.19
Man	66	268	282	262	-11	76	66	3.4	25	227	-21	75	54	3.0	11	-0.28	-0.32	63	-23	2.6	5	9.2	-51	0	1	0	-0.20	-0.26
Man	4	44	283	222	-24	99	75	2.2	9	213	-25	99	74	2.2	9	-0.23	-0.26	137	-30	1.6	5	2.9	-15	0	1	1	-0.05	-0.23
Man	76	4	284	109	-5	80	75	1.4	24	111	-4	80	76	1.4	26	-0.20	-0.18	98	-5	1.4	19	2.9	-12	0	0	0	-0.05	-0.10
Man	8	47	285	198	-10	82	72	2.4	20	190	-11	81	70	2.3	17	-0.25	-0.31	103	-21	1.9	5	4.5	-28	0	1	0	-0.05	-0.31
Man	89	276	286	153	1	73	74	2.1	50	151	-3	73	70	2.1	50	-0.16	-0.27	132	-7	2.0	21	3.9	-15	0	0	0	-0.05	-0.14
Man	4	57	287	122	-15	75	61	1.6	8	120	-15	75	60	1.6	8	-0.24	-0.33	82	-21	1.4	7	6.7	-30	0	1	0	-0.10	-0.10
Man	21	1	288	151	1	77	77	2.0	50	148	-3	77	73	1.9	43	-0.23	-0.27	136	-5	1.9	27	1.4	-9	0	0	0	-0.05	-0.12
Man	87	179	289	181	-17	110	93	1.6	10	175	-18	109	91	1.6	10	-0.13	-0.14	148	-21	1.4	8	1.6	-6	0	1	0	-0.05	-0.11
Man	22	15	290	126	-6	74	68	1.7	21	126	-6	74	68	1.7	21	-0.34	-0.35	7	-13	1.4	2	14.2	-74	1	1	0	-0.20	-0.30
Man	96	37	291	175	-16	102	86	1.7	11	168	-17	102	85	1.6	10	-0.15	-0.21	142	-19	1.5	8	1.6	-7	0	1	0	-0.05	-0.15
Man	66	334	292	171	-11	75	64	2.3	16	167	-10	75	64	2.2	16	-0.17	-0.30	142	-12	2.1	13	2.4	-10	0	0	0	-0.10	-0.09
Man	7	59	293	276	-3	85	82	3.2	50	258	-9	83	74	3.1	29	-0.14	-0.20	210	-13	3.0	18	5.9	-19	0	0	0	-0.05	-0.15
Man	4	100	294	128	-8	75	66	1.7	15	124	-9	75	66	1.7	14	-0.18	-0.16	99	-11	1.6	13	4.3	-15	0	0	0	-0.15	-0.09
Man	81	21	295	190	-7	74	67	2.6	26	185	-8	74	66	2.5	22	-0.14	-0.13	156	-10	2.4	17	4.2	-14	0	0	0	-0.05	-0.17
Man	89	142	296	159	-10	90	80	1.8	16	182	-8	92	84	2.0	21	-0.19	-0.32	106	-12	1.6	10	8.1	-27	0	0	0	-0.05	-0.16
Man	1	37	297	160	-9	82	73	2.0	18	155	-10	82	72	1.9	15	-0.16	-0.20	132	-12	1.8	12	2.3	-10	0	0	0	-0.05	-0.12
Man	76	31	298	194	-4	76	73	2.5	50	186	-11	75	65	2.5	17	-0.37	-0.43	52	-26	1.8	3	8.1	-45	0	1	0	-0.15	-0.42
Man	79	25	299	179	-10	82	72	2.2	18	174	-12	82	70	2.1	15	-0.18	-0.20	134	-14	2.1	12	4.3	-18	0	0	0	-0.05	-0.11
Man	27	49	300	199	-26	82	56	2.4	8	191	-26	81	55	2.3	7	-0.18	-0.15	119	-27	1.9	6	4.2	-18	0	1	0	-0.10	-0.13
Man	52	20	301	188	-13	77	64	2.4	14	185	-14	77	63	2.4	13	-0.16	-0.16	142	-15	2.2	10	3.0	-12	0	0	0	-0.20	-0.13
Man	1	37	302	224	-13	84	72	2.7	18	231	-12	86	73	2.7	19	-0.32	-0.48	7	-25	1.6	1	15.5	-86	1	1	0	-0.20	-0.39
Man	66	157	303	354	-10	100	90	3.5	35	351	-10	100	90	3.5	34	-0.21	-0.24	206	-17	3.4	14	9.7	-47	0	0	0	-0.10	-0.19

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						ΔT & ΔV		Warnings			Severity	
Cntrl	Drvr	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	ΔT, s	ΔV, ft/s	NHT SA	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Acc	66	79	1	150	3	80	83	1.9	50	132	-11	80	69	1.7	12	-0.33	-0.30	13	-15	1.5	2	14.4	-80	1	1	0	-0.20	-0.26
Acc	93	69	2	131	-4	93	89	1.4	31	108	-11	90	79	1.2	9	-0.16	-0.16	85	-12	1.1	8	3.5	-12	0	1	0	-0.05	-0.14
Acc	21	70	3	106	5	82	87	1.3	50	100	-9	82	74	1.2	12	-0.41	-0.35	81	-12	1.2	7	2.9	-24	0	1	0	-0.10	-0.24
Acc	61	44	4	103	4	100	104	1.0	50	103	-2	101	99	1.0	50	-0.13	-0.16	94	-3	0.9	30	6.2	-21	0	1	0	-0.05	-0.11
Acc	85	66	5	107	1	89	91	1.2	50	81	-20	90	70	0.9	4	-0.50	-0.42	27	-23	0.7	3	6.2	-59	0	0	0	-0.05	-0.11
Acc	65	66	6	120	-6	78	72	1.5	22	99	-13	76	63	1.3	8	-0.44	-0.45	42	-19	1.0	3	4.7	-42	1	1	1	-0.30	-0.43
Acc	88	186	7	117	-4	87	83	1.3	29	107	-11	86	75	1.2	10	-0.41	-0.37	47	-17	1.0	5	6.2	-48	1	1	0	-0.20	-0.41
Acc	14	24	8	95	-13	83	70	1.1	7	74	-18	81	64	0.9	4	-0.30	-0.19	39	-19	0.6	3	3.0	-21	0	1	1	-0.20	-0.27
Acc	87	116	9	106	-3	111	109	1.0	39	89	-13	110	97	0.8	7	-0.20	-0.28	69	-14	0.7	6	2.5	-13	0	1	1	-0.15	-0.22
Acc	81	36	10	118	-2	92	89	1.3	50	106	-11	93	82	1.1	10	-0.25	-0.22	78	-13	1.0	7	3.5	-18	0	1	1	-0.05	-0.20
Acc	59	66	11	66	-6	85	79	0.8	10	54	-12	84	72	0.6	5	-0.46	-0.44	17	-15	0.4	2	3.7	-43	0	1	0	-0.15	-0.17
Acc	87	192	12	204	-12	102	90	2.0	17	163	-24	101	78	1.6	7	-0.38	-0.35	52	-25	0.9	4	6.4	-48	1	1	1	-0.30	-0.40
Acc	52	23	13	96	-1	98	98	1.0	50	86	-9	98	89	0.9	9	-0.16	-0.23	72	-10	0.8	9	2.5	-11	0	1	1	-0.20	-0.95
Acc	4	100	14	93	-2	87	85	1.1	46	88	-4	86	82	1.0	20	-0.22	-0.28	6	-8	0.8	1	25.2	-86	0	1	0	-0.05	-0.16
Acc	89	245	15	115	-8	107	99	1.1	15	101	-14	106	92	1.0	7	-0.34	-0.33	65	-16	0.8	5	4.9	-38	1	1	0	-0.15	-0.19
Acc	21	40	16	69	-2	78	77	0.9	38	66	-5	78	74	0.8	14	-0.31	-0.25	48	-8	0.8	8	6.7	-27	0	1	1	-0.15	-0.21
Acc	66	94	17	180	-13	95	81	1.9	14	143	-26	93	68	1.5	6	-0.24	-0.29	97	-26	1.2	5	2.7	-15	0	1	0	-0.10	-0.15
Acc	88	207	18	79	-2	86	83	0.9	32	77	-4	86	81	0.9	18	-0.32	-0.33	59	-10	0.8	6	3.5	-21	0	1	1	-0.05	-0.26
Acc	85	69	19	54	3	92	94	0.6	50	53	0	92	92	0.6	50	-0.29	-0.38	43	-6	0.4	8	2.2	-14	0	1	0	-0.10	-0.20
Acc	66	53	20	235	-8	79	72	3.0	31	185	-25	78	53	2.4	8	-0.36	-0.44	77	-31	1.9	4	5.5	-49	0	1	0	-0.15	-0.21
Acc	43	33	21	112	-9	79	70	1.4	12	101	-13	78	66	1.3	8	-0.33	-0.28	45	-17	1.1	5	14.8	-66	0	1	0	-0.20	-0.41
Acc	89	51	22	146	-1	106	106	1.4	50	139	-9	106	97	1.3	16	-0.27	-0.38	95	-17	1.1	7	3.5	-22	0	1	1	-0.20	-0.24
Acc	76	64	23	262	-3	89	86	2.9	50	256	-7	89	82	2.9	37	-0.32	-0.37	25	-25	1.7	4	19.6	-76	0	1	1	-0.10	-0.28
Acc	96	90	24	108	-3	100	97	1.1	42	94	-13	100	87	0.9	7	-0.15	-0.27	77	-14	0.8	6	1.6	-7	0	1	0	-0.15	-0.35
Acc	80	27	25	32	-5	81	76	0.4	7	33	-4	81	76	0.4	8	-0.28	-0.35	9	-7	0.3	4	19.0	-81	0	1	1	-0.05	-0.22
Acc	89	259	26	74	-1	85	84	0.9	50	70	-5	85	80	0.8	13	-0.41	-0.37	60	-9	0.8	7	2.4	-17	1	1	1	-0.20	-0.25
Acc	89	276	27	76	1	87	88	0.9	50	75	-2	87	86	0.9	48	-0.32	-0.34	45	-9	0.8	6	7.0	-47	0	1	0	-0.05	-0.20
Acc	66	270	28	157	-4	80	76	2.0	40	141	-13	80	67	1.8	11	-0.21	-0.23	101	-16	1.6	8	4.0	-21	0	1	0	-0.20	-0.28
Acc	81	176	29	125	0	109	109	1.1	50	124	-2	109	108	1.1	50	-0.17	-0.15	119	-3	1.1	37	2.9	-11	0	1	0	-0.10	-0.19
Acc	41	54	30	118	-7	104	97	1.1	16	111	-11	103	92	1.1	10	-0.17	-0.24	78	-14	0.9	7	9.6	-37	0	0	0	-0.05	-0.08
Acc	44	149	31	213	-7	85	78	2.5	31	184	-22	84	62	2.2	8	-0.46	-0.55	22	-33	1.5	3	8.8	-76	0	1	0	-0.10	-0.17
Acc	89	230	32	169	-3	101	98	1.7	49	165	-5	101	96	1.6	34	-0.18	-0.18	154	-7	1.6	22	3.3	-14	0	1	1	-0.30	-0.44
Acc	54	107	33	166	-7	87	80	1.9	24	152	-12	86	74	1.8	13	-0.18	-0.20	133	-13	1.7	12	2.1	-7	0	0	0	-0.10	-0.09
Acc	88	165	34	119	0	95	95	1.3	0	119	0	95	95	1.3	50	-0.14	-0.18	114	-7	1.2	19	3.1	-10	0	0	0	-0.05	-0.13
Acc	65	66	35	74	-2	78	76	0.9	48	70	-5	77	72	0.9	13	-0.27	-0.34	64	-8	0.9	8	1.7	-11	0	0	0	-0.05	-0.09

Table H-1. FOT Brake Events

				Preceding Vehicle Brake On						Acc Vehicle Brake On						Event Minimums						AT & V		Warnings			Severity	
Cntl	Drv	Trip	#	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	R, ft	Rdot, ft/s	V, ft/s	Vp, ft/s	Htm, s	Ttc, s	Vdot, g	VpDot, g	R, ft	Rdot, ft/s	Htm, s	Ttc, s	AT, s	AV, ft/s	NHT S/A	Ttc	Vc Dot	Const Ax, g	Avoid Ax, g
Acc	21	48	36	125	-5	85	80	1.5	27	119	-7	85	78	1.4	16	-0.26	-0.25	101	-12	1.3	9	2.8	-15	0	1	0	-0.05	-0.16
Acc	46	104	37	184	-1	96	95	1.9	50	175	-9	96	87	1.8	20	-0.25	-0.29	147	-11	1.8	16	4.8	-29	0	0	0	-0.10	-0.16
Acc	88	206	38	81	-4	111	107	0.7	19	81	-4	110	106	0.7	20	-0.25	-0.20	76	-5	0.7	17	3.3	-21	0	0	0	-0.05	-0.10
Acc	29	23	39	114	-6	91	85	1.3	19	111	-7	91	84	1.2	16	-0.44	-0.40	90	-11	1.2	9	13.7	-54	0	1	0	-0.15	-0.21
Acc	22	98	40	60	-5	74	69	0.8	12	63	-5	75	70	0.8	13	-0.25	-0.35	9	-9	0.7	2	14.7	-75	1	1	0	-0.20	-0.29
Acc	56	34	41	108	-1	98	97	1.1	50	108	-1	98	97	1.1	50	-0.29	-0.36	77	-6	1.1	12	9.3	-40	0	0	0	-0.10	-0.21
Acc	89	263	42	85	-6	95	88	0.9	13	85	-6	95	88	0.9	13	-0.30	-0.36	64	-12	0.8	6	2.8	-19	0	1	1	-0.10	-0.20
Acc	92	40	43	128	1	103	104	1.2	50	127	0	103	102	1.2	50	-0.19	-0.27	114	-5	1.1	26	3.4	-16	0	0	0	-0.05	-0.15
Acc	75	68	44	134	-3	77	74	1.7	50	131	-5	76	72	1.7	28	-0.18	-0.15	121	-6	1.7	20	3.7	-15	0	0	0	-0.05	-0.13
Acc	47	42	45	158	-2	78	77	2.0	50	154	-5	78	73	2.0	29	-0.20	-0.20	121	-9	1.9	16	7.1	-32	0	0	0	-0.10	-0.14
Acc	78	129	46	81	-3	99	96	0.8	26	82	-3	99	96	0.8	27	-0.18	-0.31	67	-8	0.8	8	2.4	-12	0	1	0	-0.05	-0.19
Acc	89	67	47	135	-4	91	86	1.5	31	135	-5	91	86	1.5	29	-0.34	-0.35	81	-10	1.4	8	6.7	-39	0	1	0	-0.15	-0.24
Acc	76	89	48	375	-14	86	73	4.3	27	301	-28	87	59	3.4	11	-0.21	-0.26	135	-33	2.3	4	5.3	-28	0	1	0	-0.05	-0.31
Acc	5	60	49	81	-4	81	77	1.0	21	81	-4	81	77	1.0	21	-0.24	-0.26	73	-6	1.0	13	5.1	-24	0	0	0	-0.10	-0.12
Acc	11	47	50	128	-16	79	63	1.6	8	119	-17	78	61	1.5	7	-0.30	-0.27	38	-19	1.0	4	7.4	-42	0	1	0	-0.15	-0.22
Acc	89	66	51	182	-2	88	86	2.1	50	178	-5	88	83	2.0	35	-0.21	-0.27	126	-14	2.0	9	4.8	-25	0	1	0	-0.05	-0.24
Acc	6	50	52	94	-8	86	78	1.1	12	97	-8	88	80	1.1	12	-0.24	-0.14	87	-8	1.1	12	3.2	-16	0	0	0	-0.10	-0.07
Acc	73	167	53	161	-5	102	96	1.6	30	158	-7	102	95	1.6	24	-0.19	-0.19	118	-9	1.5	15	5.6	-24	0	0	0	-0.05	-0.13
Acc	92	62	54	225	0	102	102	2.2	50	223	-3	102	99	2.2	50	-0.16	-0.19	206	-6	2.2	35	4.5	-15	0	0	0	-0.05	-0.12
Acc	90	183	55	272	-2	89	86	3.1	50	260	-10	89	79	2.9	26	-0.27	-0.30	124	-26	2.3	5	7.0	-34	0	1	0	-0.10	-0.33
Acc	25	39	56	139	0	84	84	1.6	50	139	0	84	84	1.6	50	-0.19	-0.28	119	-7	1.6	17	3.3	-12	0	0	0	-0.05	-0.17
Acc	21	42	57	131	-1	86	85	1.5	50	130	-3	86	84	1.5	49	-0.24	-0.30	115	-6	1.5	21	3.9	-18	0	0	0	-0.10	-0.15
Acc	92	62	58	235	-2	110	108	2.1	50	231	-5	110	105	2.1	47	-0.18	-0.22	202	-9	2.1	24	4.0	-15	0	0	0	-0.05	-0.11
Acc	76	155	59	268	-26	89	63	3.0	10	222	-38	89	51	2.5	6	-0.49	-0.45	109	-42	2.3	5	4.3	-42	0	1	1	-0.20	-0.40
Acc	92	94	60	173	-8	103	95	1.7	21	176	-7	104	97	1.7	24	-0.28	-0.36	97	-14	1.6	9	16.4	-74	0	1	0	-0.15	-0.28
Acc	56	79	61	207	-20	91	71	2.3	10	210	-20	91	71	2.3	11	-0.32	-0.28	63	-25	1.3	3	6.7	-42	0	1	0	-0.10	-0.30
Acc	40	54	62	226	-4	100	95	2.3	50	224	-6	100	94	2.2	39	-0.18	-0.20	215	-9	2.2	25	2.7	-12	0	0	0	-0.05	-0.03
Acc	89	111	63	159	-6	94	88	1.7	26	162	-6	95	88	1.7	26	-0.29	-0.30	129	-8	1.7	18	5.1	-31	0	0	0	-0.10	-0.20
Acc	96	76	64	170	-12	99	87	1.7	15	173	-12	99	87	1.7	14	-0.23	-0.28	100	-16	1.5	9	6.2	-32	0	1	0	-0.10	-0.21
Acc	6	44	65	289	-13	93	80	3.1	22	278	-15	94	79	3.0	19	-0.17	-0.15	220	-17	2.4	15	5.8	-23	0	0	0	-0.05	-0.09
Acc	4	99	66	215	-30	105	75	2.1	7	215	-30	105	75	2.1	7	-0.32	-0.22	144	-31	1.8	6	4.2	-33	0	1	1	-0.15	-0.17
Acc	76	89	67	260	-13	87	74	3.0	19	260	-13	87	74	3.0	19	-0.19	-0.32	130	-21	2.8	6	9.0	-42	0	1	0	-0.10	-0.32