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Volume I – Study Results

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13. ABSTRACT (Maximum 200 words)
The Intelligent Cruise Control (ICC) system evaluation was sponsored by the National Highway Traffic Safety Administration (NHTSA) and based on an ICC Field Operational Test (FOT) conducted under a cooperative agreement between the NHTSA and the University of Michigan Transportation Research Institute (UMTRI). The FOT was performed in Michigan and involved one hundred-eight volunteers recruited to drive ten ICC-equipped Chrysler Concordes. Testing was initiated in July 1996 and completed in September 1997. The ICC system tested automatically maintains a set time-headway between an ICC-equipped vehicle and a preceding vehicle through throttle modulation and down-shifting (but not braking).

The Volpe National Transportation Systems Center (Volpe Center), with support from Science Applications International Corporation (SAIC), conducted the independent evaluation of the ICC for NHTSA. The overall goals were to evaluate: (1) Safety Effects of the ICC System, (2) ICC System and Vehicle Performance, (3) User Acceptance of the ICC System, and (4) System Deployment Issues.

The FOT provided three primary sources of data used in the evaluation: (1) digital data on ICC system and vehicle performance (e.g., velocity, time-headway, range) collected in deci-second intervals by an on-board data acquisition system, (2) video data from a forward-looking camera mounted on the vehicle, and (3) participant questionnaires and focus groups. The data was collected by UMTRI and was forwarded to the Volpe Center and SAIC on CD-ROM disks. A special database was established to support the evaluation. In addition, a number of data processing and analysis tools were also developed. This evaluation report describes the approaches used to address each evaluation goal, discusses detailed results and findings, and makes recommendations in each area. Volume I provides the study results and Volume II provides the supporting appendices.

With respect to the primary evaluation goal (safety), it was concluded that use of the ICC system was associated with safer driving compared to manual control and, to a lesser extent, conventional cruise control, and is projected to result in net safety benefits if widely deployed. The evaluation also uncovered some areas of safety concern associated with ICC driving. In spite of these concerns, however, there are several ameliorating factors that suggest the concerns do not represent an overall safety problem for the ICC system.

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Preface

This report presents the results of a comprehensive and independent effort to evaluate the effectiveness of an Intelligent Cruise Control (ICC) System. The ICC evaluation was sponsored by the National Highway Traffic Safety Administration (NHTSA) and based on a Field Operational Test (FOT) conducted under a cooperative agreement between NHTSA and the University of Michigan Transportation Research Institute (UMTRI). Also included in the FOT partnership were Leica AG, the Michigan Department of Transportation, and Haugen Associates. The FOT was performed in Michigan and involved one hundred-eight volunteers recruited to drive ten ICC-equipped Chrysler Concordes. Testing was initiated in July 1996 and completed in September 1997.

The Volpe National Transportation Systems Center (Volpe Center), with support from Science Applications International Corporation (SAIC), conducted the independent evaluation of the ICC system for NHTSA.

The overall goals of the evaluation were to evaluate:

1. Safety Effects of the ICC System
2. ICC System and Vehicle Performance
3. User Acceptance of the ICC System
4. System Deployment Issues

Numerous authors at both the Volpe Center and SAIC contributed to this effort. The authors are listed on the documentation page. The authors appreciate the technical guidance provided by August Burgett of NHTSA. In addition, the authors appreciate the valuable comments provided by Al Chande of NHTSA and Neil Meltzer of the Volpe Center who performed an in-house review of this report. Darbha Swaroop, of the Texas A&M University assisted in the analysis of the impact of ICC on traffic flow. He was responsible for the appendix identified under his name. Other contributors at the Volpe Center and their involvement were Howard Winkler, data base analysis; Francisco Vicenty, critical pre-crash scenario analysis; Robert DiSario, review of statistical methods and results; Raul Nieves, database development; Frank Foderaro database programming and querying; Chris Wiacek, collision database analysis; Sam Park, video analysis; and Peter Yap, state space boundary analysis. Finally, appreciation is extended to the editorial personnel, who were patient in their unending support: Stacey Curran, Robert Marville and Arthur Rubin.

The authors and contributors also wish to acknowledge the contributions Dr. Michel Van Aerde who suddenly and unexpectedly passed away on August 17, 1999. Mike not only contributed to the traffic flow analysis in Chapter 5 and the congestion model in Appendix G, but also played an important role in the development of the safety analysis framework used in this study. He will be missed by his colleagues.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC		METRIC TO ENGLISH	
LENGTH (APPROXIMATE)		**LENGTH** (APPROXIMATE)	
1 inch (in)	= 2.5 centimeters (cm)	1 millimeter (mm)	= 0.04 inch (in)
1 foot (ft)	= 30 centimeters (cm)	1 centimeter (cm)	= 0.4 inch (in)
1 yard (yd)	= 0.9 meter (m)	1 meter (m)	= 3.3 feet (ft)
1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	= 1.1 yards (yd)
		1 kilometer (k)	= 0.6 mile (mi)
AREA (APPROXIMATE)		**AREA** (APPROXIMATE)	
1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	= 0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)	1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	= 1 hectare (he) = 2.5 acres
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)		
MASS - WEIGHT (APPROXIMATE)		**MASS - WEIGHT** (APPROXIMATE)	
1 ounce (oz)	= 28 grams (gm)	1 gram (gm)	= 0.036 ounce (oz)
1 pound (lb)	= 0.45 kilogram (kg)	1 kilogram (kg)	= 2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)	1 tonne (t) = 1,000 kilograms (kg)	= 1.1 short tons
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1 teaspoon (tsp)	= 5 milliliters (ml)	1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	= 15 milliliters (ml)	1 liter (l)	= 2.1 pints (pt)
1 fluid ounce (fl oz)	= 30 milliliters (ml)	1 liter (l)	= 1.06 quarts (qt)
1 cup (c)	= 0.24 liter (l)	1 liter (l)	= 0.26 gallon (gal)
1 pint (pt)	= 0.47 liter (l)		
1 quart (qt)	= 0.96 liter (l)		
1 gallon (gal)	= 3.8 liters (l)		
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)	1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)	1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)
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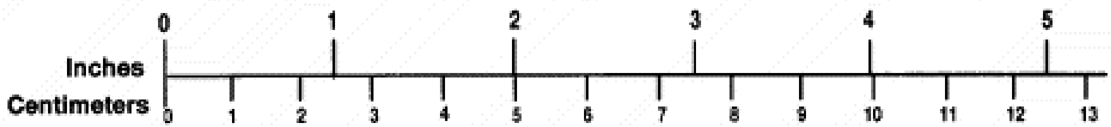

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°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Background

The Intelligent Cruise Control (ICC) system automatically maintains a set time-headway between an ICC-equipped vehicle and a preceding vehicle through throttle modulation and down-shifting (but not braking). When traffic is encountered, ICC-equipped drivers are provided the convenience of some relief from manually engaging, disengaging, or resetting velocities, as is often the case with Conventional Cruise Control (CCC). When not in traffic, ICC functions in a manner similar to CCC.

The ICC evaluation documented in this report was sponsored by the National Highway Traffic Safety Administration (NHTSA) and was based on an ICC Field Operational Test (FOT) conducted under a cooperative agreement between the NHTSA and the University of Michigan Transportation Research Institute (UMTRI). Also included in the FOT partnership were Leica AG, the Michigan Department of Transportation, and Haugen Associates. The FOT was performed in Michigan and involved one hundred-eight volunteers recruited to drive ten ICC-equipped Chrysler Concordes. Testing was initiated in July 1996 and completed in September 1997.

The Volpe National Transportation Systems Center (Volpe Center), with support from Science Applications International Corporation (SAIC), conducted the independent evaluation of the ICC system for NHTSA.

The ICC system, although intended as a user convenience system, has features that could affect safety. With the imminent commercialization of ICC-type systems in the United States, it was, therefore, important that an evaluation of ICC with a major focus on its safety effects be conducted. Although the primary goal of this NHTSA sponsored evaluation was to determine ICC system safety effects, the evaluation had other goals as well. The overall goals were to evaluate:

1. safety effects of the ICC system,
2. ICC system and vehicle performance,
3. user acceptance of the ICC system, and
4. system deployment issues.

Conclusions

1. Safety Effects of the ICC System

Use of the ICC system in the FOT was generally associated with safer driving compared to manual control, and to a lesser extent compared to CCC, and is projected to result in net safety benefits if widely deployed. This conclusion is based on assessment of various objective safety surrogate measures, driver perceptions, and modeling of the widespread deployment of ICC systems. The safety benefits of the ICC system are primarily attributable to the system's ability to maintain constant velocities and/or headways when a slower vehicle is encountered, and the pattern of ICC drivers to use the system predominately on freeways under conditions of light or moderate traffic with fewer vehicle interactions and relatively uniform velocities.

A few safety concerns were identified regarding use of ICC. These concerns were primarily associated with the tendency of some ICC drivers to wait for the system to resolve driving situations before intervening. Although these concerns deserve further attention, several ameliorating factors suggest that the potential safety risk associated with the system is far outweighed by its safety benefits.

2. ICC System and Vehicle Performance

As a prototype, the ICC system performed remarkably well both in a variety of controlled experiments on public roadways and under natural conditions driven by the FOT participants. Analysis of the FOT data shows that the ICC system adequately maintains set headways and velocities, and reduces the need for drivers to brake within the control authority of the system. The sensors reliably detect vehicle targets within the specified field of view. There were performance problems when the system was operated in rain or snow. However, these problems were not regarded as serious because they appeared related to the prototype status of the system, and it is assumed they will be addressed in future production systems.

3. User Acceptance of the ICC System

The ICC system generally had a very high level of acceptance by the FOT participants. Both prior users of CCC and non-users of CCC preferred the ICC to CCC. Participants overwhelmingly ranked ICC over CCC and manual driving for convenience, comfort, and enjoyment. Most participants indicated they would use ICC on freeways. In addition, many indicated they would use the system on 2-lane and rural roads. There was a high level of comfort in seeing ICC replace CCC in future vehicles, and participants indicated a willingness to pay about $300 for an ICC system.

4. System Deployment Issues

Under certain conditions of short time-headway settings (e.g., 1.0 second) and high velocities, ICC systems could improve roadway capacity. Longer time-headway settings (e.g., 2.0 seconds) could reduce roadway capacity. Alternative, non-linear time-headway control algorithms could improve roadway capacity beyond that of the tested system. The reduced throttle fluctuations of ICC will result in reduced fuel consumption and emissions. Projected costs of ICC systems, at 500,000 units per year are within the range of willingness-to-pay estimates.

Evaluation Approach

The FOT provided three primary sources of data used in the evaluation:

1. digital data on ICC system and vehicle performance (e.g., velocity, time-headway, range) collected in deci-second intervals by an on-board data acquisition system,

2. video data from a forward-looking camera mounted on the vehicle, and

3. participant questionnaires and focus groups.

The data collected by UMTRI was forwarded to the Volpe Center and SAIC. A special database was established to support the evaluation. In addition, a number of data processing and analysis tools were developed to support analysis of the data.

The first evaluation goal, to *Evaluate Safety Effects of the ICC System*, addressed three basic questions:

1. Did the FOT participants drive more or less safely with the ICC system than without it, in ways related to the system?

2. Did the FOT participants perceive a safety benefit from use of the ICC system?

3. What would be the effect of widespread use of the ICC system on roadway safety?

Because the FOT was not expected to result in any crashes (and, in fact, did not), a number of objective, safety surrogate measures were defined to address the first safety question. The digital and video data were used extensively to quantify the safety measures. To aid in the integration of these various measures, a *safety analysis framework* was developed. This framework permits all driving experience encountered in the FOT to be characterized in terms of states and transitions. States are defined as either closing, cruising, following, or separating. Transitions (or maneuvers) are changes from one state to another and include lane changes, cut-ins, approaches, and lead vehicle decelerations. The framework also provides a means of describing the impact of the three control modes, ICC, manual, and CCC, on driving behavior. All of the safety surrogate measures used in the evaluation were related to this analysis framework.

The second safety question, relating to driver perceptions of safety, was addressed primarily using results of the participant questionnaires. The third safety question, relating to widespread safety effects of ICC, was addressed through use of a safety benefits estimation methodology developed under NHTSA sponsorship.

The second evaluation goal, to *Evaluate ICC System and Vehicle Performance*, was based primarily on analysis of data resulting from a series of pilot tests conducted under controlled conditions by the evaluation team prior to the FOT. Participant questionnaire results were also used.

The third evaluation goal, to *Evaluate User Acceptance of the ICC System*, was based on analysis of the participant questionnaire results.

The fourth evaluation goal, to *Evaluate System Deployment Issues*, addressed impacts of the ICC system on traffic flows, impacts on fuel consumption and emissions, user willingness to pay for an ICC system, and institutional issues associated with full deployment of ICC systems. Effects on traffic flow were evaluated by applying standard traffic engineering analysis to ICC data on speed, headway, and lane change characteristics. Fuel consumption and emissions were determined using a model developed by the Center for Transportation at the Virginia Polytechnic Institute and State University and data supplied by Oak Ridge National Laboratories. Willingness to pay was based on a comparative cost analysis between Anti-Lock Braking Systems (ABS) and the potential development of ICC systems. The potential for market penetration was evaluated by analysis of the likely cost of production ICC systems, and comparison of these systems with the amount participants said they would be willing to pay for these systems.

Summary of Significant Findings

1. Evaluation Goal #1 – Evaluate Safety Effects of the ICC System

The following is a discussion of the safety surrogate measures, driver perceptions, and modeling of ICC safety benefits that supported the overall safety conclusions. As a convenience to the reader, the various indicators used for evaluating ICC safety are summarized in Table 1. The indicators apply to both freeway and arterial roadways except where noted. The table also shows how these indicators were interpreted in terms of whether they indicated a safety benefit, a safety neutrality, or a safety concern for the ICC system.

The challenge to the evaluators of the ICC system was to integrate the various indicators listed in Table 1 into an overall conclusion regarding the safety effect of ICC use. In doing this, several important observations were made:

1. An examination of the potential safety benefits yielded the following considerations:

   - there were many more indicators of potential benefits than of safety concerns,
   - these benefits accrued over most conditions that ICC drivers were exposed to, and
   - the generally positive indications of these measures were further supported by the subjective responses of the FOT participants and the analytical modeling results of widespread ICC use.

2. An examination of the safety concerns, including detailed video examination of many individual driving situations, yielded the following ameliorating considerations:

   - the driving situations causing concern were rare events to which most ICC drivers had very limited exposure,
   - the occurrence of events causing concern may decline as ICC drivers gain more experience with the system,
   - the individual safety-critical cases examined were all successfully resolved by the ICC drivers, and, therefore,
   - given the above, it was concluded that these concerns did not represent a general safety problem or indicate any inherent safety deficiency with the ICC system.

Based on the above observations, the overall conclusion of the evaluators was that use of the ICC will result in net safety benefits if widely deployed.

Table 1. Summary of Significant Safety Findings

Safety Surrogate Measure	*Indicates Safety Benefit*	*Safety Neutral*	*Indicates Safety Concern*
1. Usage	+		
2. Driving States and Transitions			
2.1 Time in Closing States (Freeways)	+		
2.2 Time in Closing States (Arterials)		0	
2.3 Time in Closing Close Sub-states (Freeways)	+		
2.4 Time in Closing Close Sub-states (Arterials)		0	
2.5 Lane Changes	+		
2.6 Cut-ins	+		
3. Overall Driving Behavior			
3.1 Time-Headway	+		
3.2 Velocity		0	
3.3 Velocity Variability (Freeways)	+		
3.4 Acceleration	+		
3.5 Acceleration Variability	+		
3.6 Braking Frequency	+		
3.7 Braking Force	+		
3.8 Response Time			-
4. Behavior in Safety-Critical Situations			
4.1 Closing Rate		0	
4.2 Time Headway (Freeways)	+		
4.3 Velocity (Freeways)			-
4.4 Braking Frequency (Freeways)	+		
4.5 Braking Force (Freeways)			-
4.6 Response Time (Freeways)			-
4.7 State Space Boundary Crossings (Freeways)	+		
4.8 Close Calls (Freeways)	+		
4.9 Close Calls (Arterials)			-
4.10 Most Severe Close Calls (Freeways)	+		
4.11 Most Severe Close Calls (Arterials)			-
4.12 Pre-crash Scenarios (Freeways)	+		
4.13 Critical Pre-crash Scenarios (Freeways)			-
5. Driver Perceptions of Safety	+		
6. Estimate of Widespread Safety Benefits	+		

1.1 Usage of the ICC System

ICC drivers in the FOT, on average, used the ICC system for 19 hours and drove about 1646 kilometers. The ICC system was used extensively on freeways, approaching 60 percent usage on trips greater than 15 minutes. This usage was about 50 percent greater than that of conventional cruise control (CCC). The ICC system was used about 6 percent of the time on arterials, about 50 percent more than CCC. The ICC system was used in greater levels of traffic congestion than CCC; e.g., 26.5 percent more than CCC in moderate levels of traffic congestion.

From a safety perspective, the usage patterns of ICC drivers would tend to promote safer driving. More specifically, ICC drivers tended to use ICC predominately on freeways under conditions of light or moderate traffic. These conditions are generally more safety-benign, involving fewer interactions with other vehicles and relatively uniform, albeit higher, velocities.

1.2 Driving States and Transitions

1.2.1 Indicators of a Safety Benefit for ICC

Time in Closing States (Freeways) – This measure indicates the amount of exposure to situations involving closings on a lead vehicle. Driving with the ICC system resulted in less proportion of time spent closing on a lead vehicle; 5.1 percent of the time for ICC versus 6.8 percent for manual and 5.2 percent for CCC.

Time in Closing Close Sub-state (Freeways) – On freeways, driving with the ICC system resulted in the least time spent in states of closing at headways under 0.8 seconds (close) compared to manual or CCC driving.

Lane Changes – This measure indicates the frequency of risky maneuvers from one situation to another, especially in response to slower traffic. The number of lane changes on freeways and arterials when using ICC is less than that for manual driving. For example, on freeways, the rate of lane changes for ICC driving was about 8 per 100 km, in contrast to about 19 for manual. (CCC was about 7). Lane changes for ICC were less likely to result in a closing state; 1.04 lane changes per 100 km of ICC driving resulted in a closing state as compared to 3.46 for manual driving and 1.57 for CCC driving. ICC lane changing also resulted in proportionately fewer instances of ending in states of closing, following, or separating at headways under 0.8 seconds (close) compared to manual driving (14 percent for ICC versus 21 percent for manual). Most importantly, ICC driving resulted in significantly fewer instances of lane changing from closing-close situations (2 percent of lane changes for ICC versus 8 percent for manual and 7 percent for CCC). This is seen as evidence that ICC driving reduces the need for drivers to make safety-critical lane changes in response to slower traffic.

Cut-ins – This measure indicates the frequency of situations where other drivers cut in ahead of the host vehicle, potentially resulting in high closing rates and short headways. The frequency of cut-ins on freeways and arterials when using ICC is less than manual driving and equal to CCC driving. For example, on freeways, the rate of cut-ins for ICC driving was about 12 per 100 km, in contrast to about 20 for manual. Furthermore, the rate of cut-ins that resulted in a closing state is also less for ICC (about 2.48 per 100 km) than for manual (about 4.42 per 100 km) and about the same for CCC (about 2.10 per 100 km). It was also found that increases in ICC headway setting, from 1.0 seconds to 2.0 seconds, did not increase the rate of cut-ins, as was hypothesized before the test.

1.2.2 Indicators that are Safety Neutral for ICC

Time in Closing States (Arterials) – Driving with the ICC system resulted in a greater proportion of time spent closing on a lead vehicle; 8.5 percent of the time for ICC versus 4.4 percent for manual and 6.5 percent for CCC. Although this could represent a safety concern, it is considered safety-neutral because of several important considerations; namely, very little time exposure is involved (only about 0.5 percent of ICC driving is in the closing state on arterials) and there is evidence that the paucity of data on arterials produced unreliable results (an alternative analysis that aggregated the data over all ICC drivers produced opposite results; i.e., ICC had the least time in closing states).

Time in Closing Close Sub-state (Arterials) – On arterials, driving with the ICC system resulted in about the same percent of time spent in states of closing at headways under 0.8 seconds (close) as manual and CCC driving.

1.3 Overall Driving Behavior

1.3.1 Indicators of a Safety Benefit for ICC

Time-Headways – Longer time-headways will provide more time for drivers (or the ICC system) to respond to traffic situations. Time-headways were longer for the ICC system than for manual driving, but less than CCC. Average time-headways for freeway driving were about 1.9 seconds for ICC compared to 1.7 seconds for manual and 2.2 seconds for CCC.

Velocity Variability (Freeways) – This measure indicates the level of velocity differences between vehicles and, thus, the likelihood of closings and other interactions resulting from responses to closings.

Variability in ICC velocity was much less than in manual driving, but more than in CCC. The average standard deviation in velocity was about 4.4 km/h for ICC compared to 11.1 km/h for manual and 2.8 km/h for CCC.

Acceleration - The spread of acceleration (positive and negative) was much wider for manual driving. Most of the ICC accelerations fell within +/- 0.05 g, whereas more manual accelerations fell outside this range.

Acceleration Variability – Acceleration variability for ICC driving was relatively low and less than that for manual driving for all velocity levels. The largest standard deviation in acceleration for manual driving was in velocities below 80 km/h.

Braking Frequency - The number of brakings per kilometer of freeway driving for ICC (about 5.0 brakings per 100 km) was significantly less than for manual (about 25.0 brakings per 100 km) and for CCC (about 12.0 brakings per 100 km). The number of brakings per kilometer of arterial roadway driving for ICC (about 31.0 brakings per 100 km) was also significantly less than for manual (about 90.0 brakings per 100 km) and for CCC (about 41.0 brakings per 100 km).

Braking Force – The distribution of different braking force levels provides an indication of the frequency of potentially dangerous interactions with other vehicles. The overall distribution of braking force versus braking frequency was significantly less for ICC than for manual (generally by more than one order of magnitude) and was more comparable to CCC. For example, the relative frequency of 0.1 g brakings on freeways per 100 kilometers traveled (at velocities greater than 80.5 km/h and with lead vehicle present) was about 0.11 for ICC compared to 0.14 for CCC and 5.00 for manual. Although the proportion of brakings at force levels 0.1 g and higher is generally greater for ICC than for manual and CCC, the actual rate of brakings (brakings per million kilometers) in these higher force levels is consistently less for ICC than for manual.

The overall distribution of braking force versus braking frequency on arterials was significantly less for ICC than manual. However, the proportion of brakings at force levels 0.1 g and higher is generally greater for ICC than for manual and CCC. This latter finding is consistent with the concern expressed elsewhere that ICC drivers tend to wait for the system to control situations and, therefore, intervene later when necessary. Although this is a concern, the higher braking force events are extremely rare (only 39 braking events at 0.30 g or higher were detected for ICC system on arterials).

1.3.2 Indicators that are Safety-Neutral for ICC

Velocity – Higher velocities increase the potential for encountering closing situations with slower lead vehicles and the severity of crashes. ICC velocities tended to be less than CCC, but more than manual. Average velocities on freeways were as follows: ICC = 106 km/h, manual = 96 km/h, CCC = 110 km/h. The velocity differences were interpreted to be the result of the different traffic conditions under which drivers choose to drive manually or with cruise control. This measure was interpreted as indicating no particular benefit, or disbenefit, for ICC.

1.3.3 Indicators of a Safety Concern for ICC

Response Times – This measure provides an indication of driver inattentiveness and/or increased potential for reduced headways and higher closing rates with lead vehicles. Driver responses to the brake light stimulus of a lead vehicle were generally longer in ICC driving than manual, by about 0.3 seconds, but slightly less than CCC. The longer response times in ICC (and CCC) appear due, in part, to longer time-headways for these systems and drivers taking advantage of these longer times to delay responding. Although, there was no clear evidence that the longer responses were due to inattentiveness, the possibility of inattentiveness cannot be ruled out for all situations. However, based on the video analysis as well as participant questionnaires and focus groups, drivers seemed to be well aware of evolving situations. In fact, a pattern emerged from the analysis suggesting that drivers with ICC tended to wait for the system to respond to given situations to avoid disengagement and, hence, intervened later than would be the case in manual operation. In general, the later interventions did not result in critical situations.

1.4 Driving Behavior in Safety-Critical Situations (Closing and Pre-Crash Scenarios)

1.4.1 Indicators of a Safety Benefit for ICC

Time-Headway (Freeways) - Time-headways in closing situations were slightly longer for the ICC system than for manual and CCC driving. Average time-headways for freeway driving were about 1.7 seconds for ICC compared to 1.5 seconds for manual and 1.6 for CCC.

Braking Frequency (Freeways) – During closing events, there were generally fewer brakings at each braking force level for ICC than for manual, although at force levels greater than 0.30 g the frequency was about equal.

State Space Boundary Crossings (Freeways) - This measure provides an indication of the frequency of interactions with other vehicles, especially in high closing rate and short headway situations. The frequency of encountering such situations per kilometer of freeway traveled was much less for ICC than for manual and CCC. For example, situations that would have required the host vehicle to decelerate at a constant rate of 0.10g to avoid a minimum headway of 4 m with a lead vehicle was encountered with a frequency of about 4.0 per 100 kilometers for ICC in contrast to about 6.0 for CCC, and about 14.0 for manual.

Close Calls (Freeways) – This measure indicates the frequency of potentially dangerous interactions with other vehicles. The frequency of "close calls" on freeways per 100 kilometers traveled for ICC (3.4) was about half that for manual driving (6.2) and about equal to CCC.

Most Severe Close Calls (Freeways) – The frequency of the most severe category of close calls on freeways per 100 kilometers traveled for ICC (0.2) was substantially less compared to manual driving (0.5), but greater than for CCC driving (0.1).

Pre-crash Scenarios (Freeways) – This measure indicates the frequency of occurrences of specific types of rear-end pre-crash scenarios. ICC driving resulted in 45 to 70 percent fewer pre-crash scenarios than manual driving depending on the type of scenario, and about the same frequency as CCC. Pre-crash scenarios analyzed included lane changes, cut-ins, approaches and lead vehicle decelerations.

1.4.2 Indicators that are Safety-Neutral for ICC

Closing Rate – This measure indicates the differential velocity between the host vehicle and a preceding vehicle and, thus, the relative likelihood of a rear-end crash. The closing rate was slightly lower for ICC than for manual or CCC on freeways. On arterials, the closing rate for ICC was slightly higher than manual. Overall, in terms of closing rate, the ICC system was considered safety-neutral relative to manual driving.

1.4.3 Indicators of a Safety Concern for ICC

Velocity (Freeways) – The mean velocity of ICC on freeways during closing situations was about 11 km/h higher than manual and about equal to CCC. The higher velocities for ICC, however, did not result in shorter headways or higher closing rates and, thus, an increased probability of a crash.

Nevertheless, the velocity result was considered a safety concern since the severity of a crash, if it occurred, could be increased.

Braking Force (Freeways) – The proportion of brakings at higher force levels was higher for ICC than for manual at levels above 0.10 g. This is a safety concern for ICC as it indicates that during closings, braking with ICC was more apt to be harder than braking with Manual or CCC.

Response Time (Freeways) - Driver responses to the brake light stimulus of a lead vehicle, in critical situations of short headways, high levels of lead vehicle deceleration, and large velocity reductions of the host vehicle, were slightly longer for ICC driving than for manual, but slightly less than for CCC. Although the response times in ICC (and CCC) were longer, evidence from driver questionnaires suggests that ICC drivers are well aware of closing events and not inattentive, and results of the critical scenario and video analyses suggest that only in extremely rare situations do drivers wait so long that severe braking is required. The response time analysis is therefore viewed as a safety concern, but not an indication of a general safety problem for the ICC system.

Close Calls (Arterials) - ICC driving on arterial roadways generally resulted in a greater rate of close calls than for manual or CCC driving. The average number of close calls per 100 kilometers of travel on arterials was over 5.0 for ICC and CCC, about 2.5 times that of manual driving. The high average rate of close calls when ICC was used was not representative of the majority of drivers who used ICC on arterials. Of those who used ICC on arterials, 40 percent had no close calls. However, a third of the drivers had an extremely high rate of close calls and raised the overall average to high levels. Although this is a safety concern, it is confined to a subset of drivers, and from the perspective of safety exposure, ICC was used only about 6 percent of the time when driving on arterial roadways. This was, therefore, not deemed a general safety problem for the ICC system.

Most Severe Close Calls (Arterials) – When analyzing only the most severe category of close calls, the same trend of higher ICC frequency for a subset of drivers on arterials was seen. The frequency of most severe close calls on arterials for ICC was about 2.2 per 100 kilometers traveled, versus 0.9 for manual and 1.6 for CCC.

Critical Pre-Crash Scenarios (Freeways) –Video examinations were made of 41 events that had the highest braking levels or near encounters in the FOT. These 41 events were then classified into pre-crash scenario groups. Of the 41 events, 20 involved driving with the ICC system, 14 involved use of CCC, and 7 involved manual driving.

All cases that indicated a safety concern for ICC resulted from drivers appearing to wait for the ICC system to respond to an evolving situation to avoid disengagement and then intervening late, braking at a high level, to successfully resolve the situation. This is essentially the same phenomenon noted above in the response time discussion. The video analysis concluded that, although the ICC driver may have contributed to the severity of situations by waiting longer to intervene, none of the situations indicated a general safety problem for the ICC system. It was also noted that the ICC situations may have involved a learning component; i.e., the ICC drivers were learning how best to use the system and that the critical situations noted might decline with more experience.

1.5 Driver Perceptions of ICC Safety

Field test participants, overall, ranked manual driving most safe, ICC next, and CCC least. However, drivers said they drove most cautiously with ICC and agreed that ICC would improve safety. Drivers also said they felt safe using the ICC system.

1.6 Estimated Safety Benefits of Widespread ICC Use

If ICC systems were to be fully deployed and used at the levels in the FOT, it is estimated that the number of collisions on freeways would be reduced by 17 percent for two specific types of collisions: (1) ICC vehicle approaching a slower vehicle traveling at a constant velocity, and (2) a lead vehicle decelerating in front of an ICC vehicle. Although not estimated under this current effort, additional safety benefits from ICC use would be expected from a reduction in other rear-end collisions involving cut-ins and lane changes, and from use of ICC on roadways other than freeways.

2. Evaluation Goal #2 – Evaluate ICC System and Vehicle Performance

2.1 ICC Sensors

The ICC sensors were able to detect vehicle targets within the specified field of view and were adequate for freeway conditions. The sensors also measured distances very accurately. The field of view extended to 133 m, but reliable detection of targets extended to about 100 m. There was some loss of targets on the curves and hills of secondary roads and ramps but not sufficient to degrade overall performance. In severe rain, the system automatically shut down, as designed, when backscatter from rain was excessive. The system did not perform well in snow because snow would accumulate on the bumper and sometimes generate false negatives as the snow scattered signals from the lead vehicle. In other instances, the snow on the bumper would generate false positives as it reflected signals directly back to the sensors. Because of its prototype status, these are understandable performance problems, but would need to be addressed prior to commercialization.

2.2 ICC Driver Interface

The driver interface was generally well received by participants. The low visibility buzzer, indicating sensor backscatter during rain and snow, was found annoying by some.

2.3 Integrated ICC and Vehicle Performance

As a prototype, the ICC system performed remarkably well for the FOT participants driving on public roadways, both in a variety of controlled experiments and under natural conditions. Analysis of the FOT data shows that the ICC system adequately maintains set headways and velocities, and reduces the need for drivers to brake within the control authority of the system. There were performance problems when the system was operated in rain or snow. However, these problems were not regarded as serious because they appeared related to the prototype status of the system. The system was less aggressive in accelerating to close gaps than in decelerating to extend gaps. This tended to increase headway gaps beyond the set headway. Drivers noted that they would have desired more acceleration capability.

3. Evaluation Goal #3 – Evaluate User Acceptance of the ICC System

The FOT participants expressed a strong level of acceptance of the ICC. Both prior users of CCC and non-users of CCC preferred the ICC to CCC. Participants overwhelmingly ranked ICC over CCC and manual for convenience, comfort, and enjoyment.

Participants, particularly those who had the ICC system for only one week, indicated that they would be more comfortable with the system given more time. This indicated that ICC driving introduced a sufficiently new dimension to driving that the participants required more than a week of experience to be fully comfortable with the system. This suggests that special orientation and training of future ICC users might be appropriate.

Participants indicated they would most likely use ICC on freeways. However, a significant number would also use it on 2-lane and rural roads where they indicated they were comfortable using it. This suggests that future ICC systems should be designed with their use on secondary roads in mind (for example by accommodating narrow lanes, sharp curves, and steeper hills).

There was a high level of comfort in seeing ICC replace CCC in future vehicles and median estimates of willingness to pay ranged from $275.00 by those who do not use conventional cruise control to $475.00 by current users of conventional cruise control.

4. Evaluation Goal #4 – Evaluate System Deployment Issues

4.1 ICC Effects on Traffic Flows

Under certain conditions of short time-headway settings (e.g., 1.0 second) and high velocities, ICC systems could improve roadway capacity. Longer time-headway settings (e.g., 2.0 seconds) could reduce roadway capacity. Alternative, non-linear time-headway control algorithms could improve roadway capacity beyond that of the tested system. Also, alternative algorithms could reduce the impact on traffic flows of instabilities caused by multiple ICC-equipped vehicles traveling in platoons.

4.2 ICC Effects on Fuel Consumption and Emissions

Use of the ICC system reduces throttle fluctuations and, thus, the frequency and magnitude of accelerations. These factors will result in reduced fuel consumption and emissions for ICC driving.

4.3 Projected ICC Costs

Projected costs of ICC systems at a market penetration level of 500,000 units per year fall within the range of the average willingness-to-pay of between $275 and $475, determined from the participant questionnaire.

4.4 Institutional Issues

The study identified two issues directly relevant to future deployment of ICC-like systems: (1) ICC standards and (2) instruction of new ICC users. Participants indicated that the Government should be involved in developing standards for these systems and that the lack of standards for ICC technology might adversely affect their development. Also, there was some consensus that the development of instructional materials would be useful to help ensure that new users of ICC operate the system appropriately.

Recommendations

Beyond the conclusions and results discussed above, the following recommendations are made for further consideration:

1. Safety Effects of ICC Systems

1.1 Further research into ICC systems with higher deceleration authority seems warranted. Systems with braking authority up to a range of 0.2 g to 0.3 g would automatically resolve all but the rarest of events observed in the FOT. Such systems would eliminate most of the situations where the driver waited for the system and then had to intervene late to exercise additional braking. The dilemma such a system creates, however, is that the driver may become over-reliant on the system and may not be prepared to intervene in extremely rare situations when it is required. Research in this area should, therefore, also include the need for supplementary driver warnings, control algorithms for effective ICC control in braking situations, and human factors issues.

1.2 As was observed in the FOT, use of the ICC system on roadways other than freeways, such as arterials, created some safety concerns. Techniques to mitigate potential hazards of using ICC on non-freeways should be investigated. Possible solutions might involve the development of instructional techniques for new ICC users, means for inhibiting the operation of ICC on non-freeways, and/or tailoring the performance of ICC systems to meet the unique operational requirements of non-freeway driving.

1.3 Use of the ICC seemed to place new demands on the driver that required some adjustment time for drivers. This was noted in the driver questionnaires, the institutional analysis, and in observation of videos. A concern this raises is that new drivers could use the system in ways that are inappropriate and potentially hazardous. Development of effective techniques for orientation and training of new ICC users to assist in the learning process is therefore suggested as an area of future research.

2. ICC System Performance

Marketable ICC systems should address shortcomings identified in the FOT, particularly the effects of snow. In addition, to the extent that ICC will be used on secondary roads, the systems will need to function well under these more difficult roadway geometries.

3. Deployment Issues

More research is needed on the effects of widespread deployment of ICC on traffic flows. In particular, the effects of time-headway settings, algorithms for controlling headways, and multiple ICC vehicles in platoons on traffic flows should be investigated.

4. Supporting Research

4.1 The ICC FOT produced extensive data on the performance of the ICC system, as well as the manual driving characteristics of a variety of drivers under a range of normally encountered traffic conditions. This is extremely useful information for researchers and system developers. The data from the ICC FOT should be made readily available to the public in a format that is convenient to support a wide range of uses.

4.2 To support the ICC evaluation, a number of data processing and analysis tools were developed. These are documented in this study and should be made available to the public to support related research.

4.3 An extremely challenging technical problem that confronted the evaluators was to develop techniques for identifying driving scenarios (e.g., cut-ins, lead vehicle decelerations) from a stream of digital data. Significant progress was made, but further research is required to perfect and standardize the techniques to provide a uniform means for evaluating future collision-avoidance systems.

1. Introduction

This document presents the results of a comprehensive evaluation of the Intelligent Cruise Control (ICC) system. The ICC system automatically maintains a set time-headway between an ICC-equipped vehicle and a preceding vehicle through throttle modulation and down-shifting (but not braking). When traffic is encountered, ICC-equipped drivers are provided the convenience of some relief from manually engaging, disengaging, or resetting velocities, as is often the case with Conventional Cruise Control (CCC). When not in traffic, ICC functions in a manner similar to CCC. With the imminent commercialization of ICC-type systems in the United States, it was appropriate that an evaluation of ICC with a major focus on its safety impacts be conducted.

1.1 Background

The National Plan for Intelligent Transportation Systems (ITS) is a major initiative of the U.S. Department of Transportation (DOT) to promote the use of advanced technologies for the purpose of improving the safety, capacity, and mobility of the nation's highways. The National Highway Traffic Safety Administration (NHTSA) is a key DOT participant in the ITS program since many of the ITS projects can potentially contribute to NHTSA's mission of improving highway vehicle safety. The ICC system, while intended as a user convenience system, has features which could affect safety. These safety effects could be positive or negative since the ICC system exercises limited control over vehicle velocities and headways, and interacts with the driver. The primary purpose of NHTSA in sponsoring this evaluation of the ICC system is, therefore, to determine its effect on safety.

Evaluation of the ICC system also supports other NHTSA safety improvement efforts such as the development of rear end collision avoidance systems. The ICC system has several features that are similar to rear end collision avoidance systems: a forward-looking sensor system for monitoring lead vehicle velocity and headway, and a means of adjusting the host vehicle velocity to maintain appropriate headways. The velocity-adjusting feature of the ICC, furthermore, serves as a warning to the driver of an approach to a slower vehicle, a function provided by rear end collision warning systems. The ICC evaluation was intended to provide information that may be useful to developers who are incorporating ICC features into forward collision avoidance and forward collision warning systems. In addition, much data was gathered during the FOT that can be used to characterize normal driving; that is, driving done without the influence of ICC or done with current technology CCC systems. This information may be useful in evaluation of the benefits of many prospective ITS systems.

The primary goal of the NHTSA-sponsored evaluation of the ICC system was to determine its safety effects. However, the evaluation also addressed three additional goals. The overall set of evaluation goals were to:

1. evaluate safety effects of the ICC system,
2. characterize ICC system and vehicle performance,
3. evaluate user acceptance of the ICC system, and
4. evaluate system deployment issues.

The Volpe National Transportation Systems Center (Volpe Center), with support from Science Applications International Corporation (SAIC), conducted the ICC evaluation for NHTSA.

The ICC evaluation was based on, and coordinated with, an ICC Field Operational Test (FOT) conducted under a cooperative agreement between the NHTSA and the University of Michigan Transportation Research Institute (UMTRI). Also included in the FOT partnership were Leica AG, the Michigan Department of Transportation, and Haugen Associates.

1.2 Intelligent Cruise Control Field Operational Test — An Overview

Ten 1996 Chrysler Concordes were equipped with the ICC system. The Concordes were factory-equipped with a conventional cruise control system. The CCC interface consisted of ON/OFF, SET/COAST, ACCelerate/RESume, and CANCEL buttons on the steering wheel hub. UMTRI added a Leica sensor and electronic box (E-Box) that performed the ICC functions. The ICC functions provided the driver with a selection of three time-headway settings. When the system was engaged, if a vehicle preceded the ICC host vehicle and was traveling at less than the selected cruise velocity of the ICC host, the host vehicle automatically adjusted its velocity such that it maintained a constant time gap between it and the preceding vehicle. The ICC system is further described in Chapter 2 of this report.

One hundred-eight volunteers were recruited to drive the ICC-equipped Concordes. Twenty-four drivers received vehicles for five weeks, and 84 received vehicles for two weeks. Testing was initiated in July 1996 and completed in September 1997.

1.2.1 Field Operational Test Objectives

Objectives of the FOT, as expressed by the UMTRI team (Fancher, Ervin, Sayer, Hagan, Bogard, Bareket, Mefford and Haugen, (1997), were to:

- evaluate system safety,
- evaluate user satisfaction,
- provide input to the designers of production systems,
- identify design and performance issues that may require further development, market research, industry standards and practices, or changes in public policy,
- contribute to the process that leads to deployment,
- understand how the individual ICC functions contribute to safety and convenience, and
- determine how drivers use ICC functions.

1.2.2 Field Operational Test Participants

The purpose of the FOT was to provide researchers with an opportunity to observe use of the ICC system by drivers who were representative of the general driving population. Furthermore, it was intended that the evaluation of the ICC system be non-intrusive and that the drivers operate the system in their normal day-to-day driving.

To assist in locating representative drivers, the Michigan Secretary of State (Michigan's driving license bureau), made available a database of 3000 licensed drivers from eight counties in South Eastern Michigan. From this database, drivers who met age and gender criteria were contacted by postcard to solicit their participation. Individuals who responded to the postcard were contacted by telephone. Towards the end of the FOT, an advertisement was run in an Ann Arbor newspaper to solicit additional volunteers between 60- to 70-years-of-age. In particular, the advertisement was intended to fill recruitment goals for older females who said that they currently used conventional cruise control, and older males who said that they did not use conventional cruise control. Participants received $150 for participating in the project. In addition, participants who returned to take part in a focus group were provided with an additional $40 compensation.

The recruited drivers represented three age groups: 20 to 30; 40 to 50; and 60 to 70 years of age. The drivers represented two populations of cruise control users; those who said they did not use cruise control, and those who said they did. Among the drivers who participated for two weeks, half stated that they regularly use conventional cruise control. The other half stated that they do not use cruise control. All the drivers who participated for five weeks stated that they regularly use conventional cruise control. Table 1-1 shows the number of drivers in each cell of the research design, and also shows that each gender was equally represented across cells.

Table 1-1 Driver Sample Size as a Function of Age Group, Previous Cruise Control Use, Weeks of Participation, and Gender

Age	Cruise Control Use	Gender	Participation 2 Weeks	Participation 5 Weeks	Total
20-30	Nonuser	Female	7		7
		Male	7		7
	Nonuser Subtotal		14		14
	User	Female	7	4	11
		Male	7	4	11
	User Subtotal		14	8	22
20-30 Subtotal			28	8	36
40-50	Nonuser	Female	7		7
		Male	7		7
	Nonuser Subtotal		14		14
	User	Female	7	4	11
		Male	7	4	11
	User Subtotal		14	8	22
40-50 Subtotal			28	8	36
60-70	Nonuser	Female	7		7
		Male	7		7
	Nonuser Subtotal		14		14
	User	Female	7	4	11
		Male	7	4	11
	User Subtotal		14	8	22
60-70 Subtotal			28	8	36
Grand Total			84	24	108

The participant orientation began with a 12-minute video that introduced the vehicle, the ICC system, and the conditions for participation. During the video presentation, a research assistant was present to answer questions. An UMTRI staff member accompanied the participants on a demonstration drive that included travel on interstate and state highways. The participants were informed that the cruise control system would operate conventionally during the first week they had the vehicle. They were further instructed that after the first week, only ICC functions would be available. An ICC system manual was kept in each vehicle. The participants were instructed on how to use the cellular phone to contact the ICC help desk.

At the end of their participation, drivers were given a questionnaire that addressed most of the evaluation objectives associated with user acceptance and perceived benefits of the ICC system. The questionnaire can be found in Appendix C of the UMTRI Interim Report (Fancher, Ervin, Sayer, Hagan, Bogard, Bareket, Mefford and Haugen, 1997).

1.3 Evaluation of the ICC System – An Overview

For each of the four goals addressed by the evaluation, a set of more specific evaluation objectives was established. These evaluation goals and objectives are listed in Table 1-2 below.

Table 1-2 Evaluation Goals and Objectives

Goals	***Objectives***
Evaluate Safety Effects	• Determine whether drivers drive more or less safely with the ICC system than without it, in ways related to the system. • Determine whether drivers perceive a safety benefit from use of the ICC system. • Assess whether widespread use of the ICC system would affect highway safety.
Characterize ICC System and Vehicle Performance	• Characterize sensor performance. • Characterize the driver interface. • Characterize integrated ICC system performance.
Evaluate User Acceptance of the ICC System	• Assess whether drivers like the ICC system. • Assess willingness to pay for an ICC system.
Evaluate System Deployment Issues	• Assess potential effects of ICC-like systems on traffic flow. • Assess potential effects of the ICC system on fuel consumption and emissions. • Assess willingness to pay for ICC-like systems. • Assess institutional issues associated with full deployment of ICC.

The FOT provided three primary sources of data used in accomplishing the evaluation goals and objectives:

1. digital data on ICC system and vehicle performance (e.g., velocity, time-headway, range) collected in deci-second intervals by an on-board data acquisition system,

2. video data from a forward-looking camera mounted on the vehicle, and

3. participant questionnaires and focus groups.

The data collected by UMTRI was forwarded to the Volpe Center and SAIC. A special database was established to support the evaluation. In addition, a number of data processing and analysis tools were developed to support analysis of the data.

The first evaluation goal, Evaluate Safety Effects, addressed three basic questions:

1. Did the FOT participants drive more or less safely with the ICC system than without it, in ways related to the system?

2. Did the FOT participants perceive a safety benefit from use of the ICC system?

3. What would be the effect of widespread use of the ICC system on roadway safety?

Because the FOT was not expected to result in any crashes (and, in fact, did not), a number of objective, safety surrogate measures were defined to address the first safety question. These safety performance measures are listed below in Table 1-3 together with the independent variables. The digital and video data were used extensively to quantify and evaluate these safety measures. To aid in the integration of these various measures, a *safety analysis framework* was developed. This framework permits all driving experiences encountered in the FOT to be characterized in terms of driving states and transitions. States are defined as either closing, cruising, following, or separating. Transitions (or maneuvers) are changes from one state to another and include lane changes, cut-ins, approaches, and accelerations/decelerations. All of the safety surrogate measures used in the evaluation were related to this *safety analysis framework*.

Table 1-3 Measures of Safety, Performance, and Independent Variables

GOAL: Evaluate Safety Effects **OBJECTIVE**: Determine whether drivers drive more or less safely with the ICC system than without it, in ways related to the ICC system.		
SAFETY MEASURE CATEGORY	**MEASURES OF SAFETY PERFORMANCE**	**INDEPENDENT VARIABLES**
Usage	Overall Exposure Time Driven Distance Driven	Cruise Control Mode Roadway Type Level of Service (Congestion) Trip Duration Age Group Week into Test Prior Cruise Control Experience Weeks of Participation Velocity Setting
Driving States and Transitions	Driving States: • Closing • Following • Separating • Cruising Driving Sub-states: • Close/Middle/Far • Rapidly/Moderately Driving Transitions: • Acquisition/Switch/Drop/ • Acceleration/Deceleration (Active/Passive) Driving Maneuvers: • Lane Change/Cut-in	Cruise Control Mode ICC Headway Setting Roadway Type
Overall Driving Behavior	Time-Headway Velocity Velocity Variability Acceleration Acceleration Variability Braking Frequency Braking Force Response Time	Cruise Control Mode ICC Headway Setting Roadway Type Age Group Prior Cruise Control Experience Weeks of Participation
Driving Behavior in Safety-Critical Situations	Closing States: • Closing Rate • Time-Headway • Velocity • Braking Frequency • Braking Force • Response Time • State Space Boundary Crossings • Close Calls Pre-Crash Scenarios: • Occurrence • Critical Braking Events • Critical Near-Encounter Events • Critical Scenarios	Cruise Control Mode ICC Headway Setting Roadway Type Level of Service (Congestion) Level of Time-Headway Level of Lead Vehicle Deceleration Level of Host Vehicle Velocity Reduction Age Group Pre-Crash Scenario Type

The second safety question, relating to driver perceptions of safety, was addressed primarily using results of the participant questionnaires. The third safety question, relating to widespread safety effects of ICC, was addressed through use of a safety benefits estimation methodology developed under NHTSA sponsorship.

The second evaluation goal, ICC System and Vehicle Performance, was based primarily on analysis of data resulting from a series of pilot tests conducted under controlled conditions by the evaluation team prior to the FOT. Participant questionnaire results were also used.

The third evaluation goal, User Acceptance of the ICC, was based on analysis of the participant survey results.

The fourth evaluation goal, Deployment Issues, addressed impacts of the ICC system on traffic flows, impacts on fuel consumption and emissions, user willingness to pay for an ICC system, and institutional issues associated with full deployment of ICC systems. Effects on traffic flow were evaluated by applying standard traffic engineering analysis to ICC data on velocity, headway, and lane change characteristics. Fuel consumption and emissions were evaluated using a model developed by the Center for Transportation at the Virginia Polytechnic Institute and State University and data supplied by Oak Ridge National Laboratories. Willingness to pay was based on a comparative cost analysis between Anti-Lock Braking Systems (ABS) and the potential development of ICC systems. The potential for market penetration was evaluated by analysis of the likely cost of production ICC systems, and comparison of these systems with the amount participants said they would be willing to pay for these systems.

Chapter 2 introduces the evaluation with a description of the ICC and data acquisition systems, and a characterization of the ICC system and vehicle performance (Evaluation Goal #2). Chapter 2 is also intended to provide the reader with a good understanding of the ICC system which is further evaluated in subsequent chapters.

Chapter 3 presents the extensive analyses which were performed to evaluate the safety effects of the ICC system (Evaluation Goal #1).

Chapter 4 presents the analyses of survey questionnaires which were administered to the ICC participants as a means of evaluating user acceptance of the ICC system (Evaluation Goal #3).

Chapter 5 presents the analyses that were performed to evaluate the wide-scale deployment issues of traffic flow impacts, fuel consumption and emissions, institutional factors, and projected ICC costs (Evaluation Goal #4).

Chapters 6 and 7 provide an overall discussion of results and a summary of conclusions, respectively.

Extensive use is made of appendices to minimize the volume of material in the main report. These appendices are referred to, as appropriate, in the main report.

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2. Characterization of ICC System and Vehicle Performance

The primary purpose for characterizing the ICC system and vehicle performance was to better understand:

- the overall system as an aid to interpreting the field test results, and
- the nature and quality of the data collected from the field.

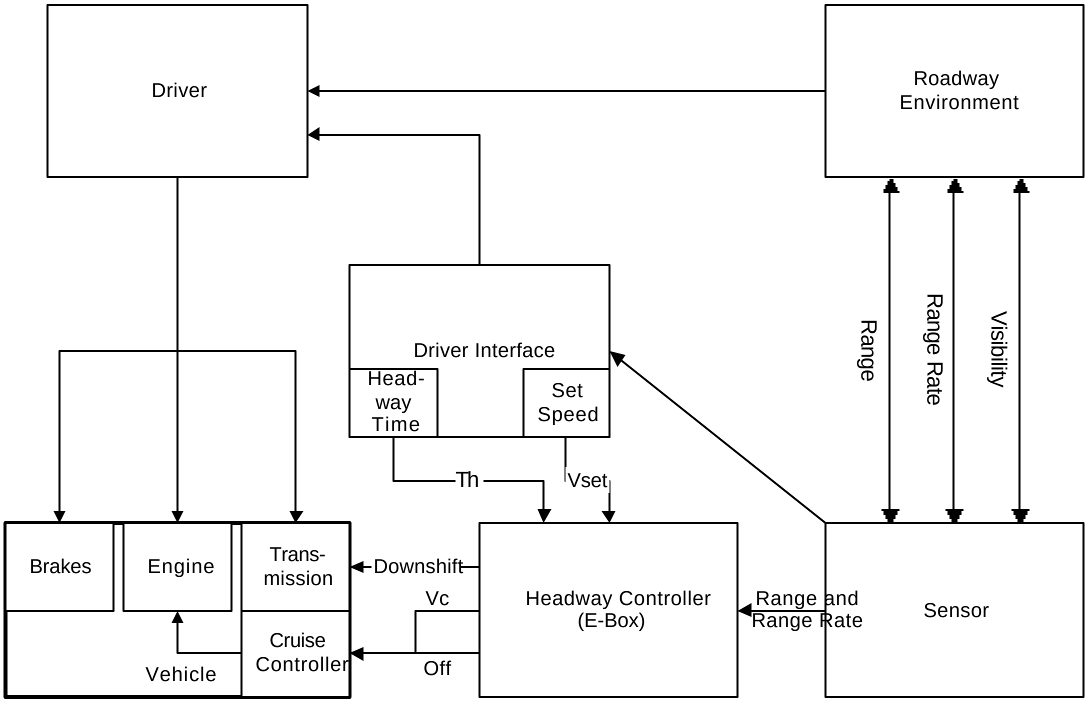
Other evaluation objectives addressed by characterizing the ICC system and vehicle performance were to support:

- development of a vehicle "state" and "transition" model,
- development of the capability to identify lane changes,
- calibration of a model for estimating fuel consumption and emissions,
- calibration and verification of map-matching software to identify road class and land use, and
- calibration and verification of a model that could be used to classify roadway levels of service.

2.1 ICC System Overview

Figure 2-1 shows the basic relationships between the driver, vehicle, environment, and ICC headway controller. The ICC system was designed as a convenience to the driver in monitoring the roadway environment and controlling the vehicle. The ICC sensor was capable of monitoring three aspects of the roadway environment: range to a preceding vehicle, closing velocity (range rate) and atmospheric visibility. The ICC driver interface enabled the driver to indicate to the system a desired travel velocity and a desired time-headway to the preceding vehicle should a slower vehicle be encountered in the ICC vehicle's lane of travel. Based on the driver's settings and sensor inputs, the ICC system controlled vehicle velocity and headway by computing throttle commands and, for additional deceleration authority, downshift requirements. The ICC driver was responsible for overall control of the vehicle and occasionally had to override the ICC system to take appropriate actions beyond the capability of the ICC system.

If the ICC system determined that visibility in the infrared range was too low for it to function properly, a low visibility warning was triggered. Fog, road spray, rain, dust or other particulates could cause low visibility. When the system deemed visibility too low for reliable target detection while the ICC system was engaged, a buzzer sounded for 2 seconds and the throttle was released. A low visibility indicator lamp was also illuminated. In those situations the driver was effectively forced to drive in manual mode until the low visibility indicator went off.



Adapted from UMTRI *Test Definition and Project Plan* (1996)

Figure 2-1 Conceptual Diagram of ICC System

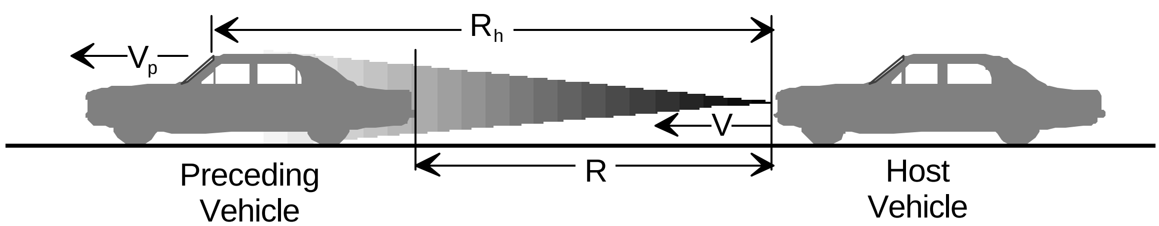
Figure 2-2 provides a sketch that shows the parameters used in headway control. These parameters were:

V_p Velocity of the preceding vehicle,

R_h Desired headway; a distance that varies with velocity and is derived from the driver's time-headway (T_h) selection,

R Actual distance headway or Range, and

V Velocity of host (ICC equipped) vehicle.



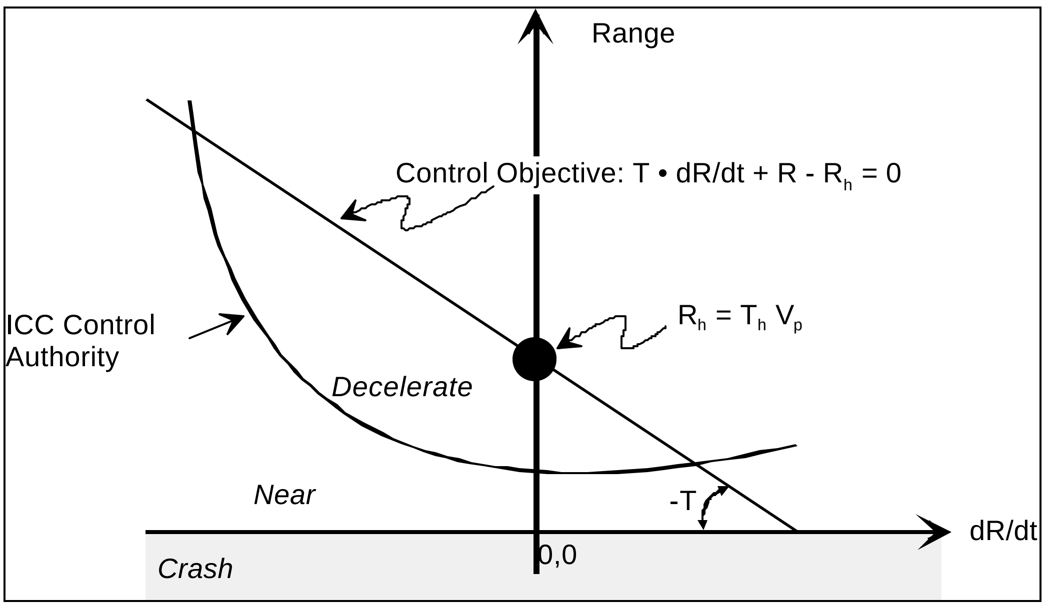
Adapted from UMTRI Test Definition and Project Plan(1996)

Figure 2-2 Headway Control Principles

Figure 2-3 shows how the ICC system headway controller worked. A range (R) and range rate (dR/dt) space is depicted. The space corresponds to the R and dR/dt information provided by the sensor. Range rate is the difference between the velocity of the preceding vehicle and the velocity of the host vehicle, i.e.,

$$dR/dt \stackrel{\Delta}{=} \dot{R} = V_p - V\ .$$

Based on where a sensor reading fell in the range, range rate space, the control algorithm determined a velocity command (V_c). How close the ICC vehicle could come to the control objective depended on the amount of control authority, and the amount of discrepancy between the reading and the objective. The figure shows the control objective function as a diagonal line. A parabola that represents the level of deceleration control authority is also shown. The point at $R = R_h$ and $dR/dt = 0$ represents the steady state control objective. The value of R_h is equal to the product of the set headway time (T_h) and the velocity of the preceding vehicle (V_p). Hence, the headway distance varied with velocity.

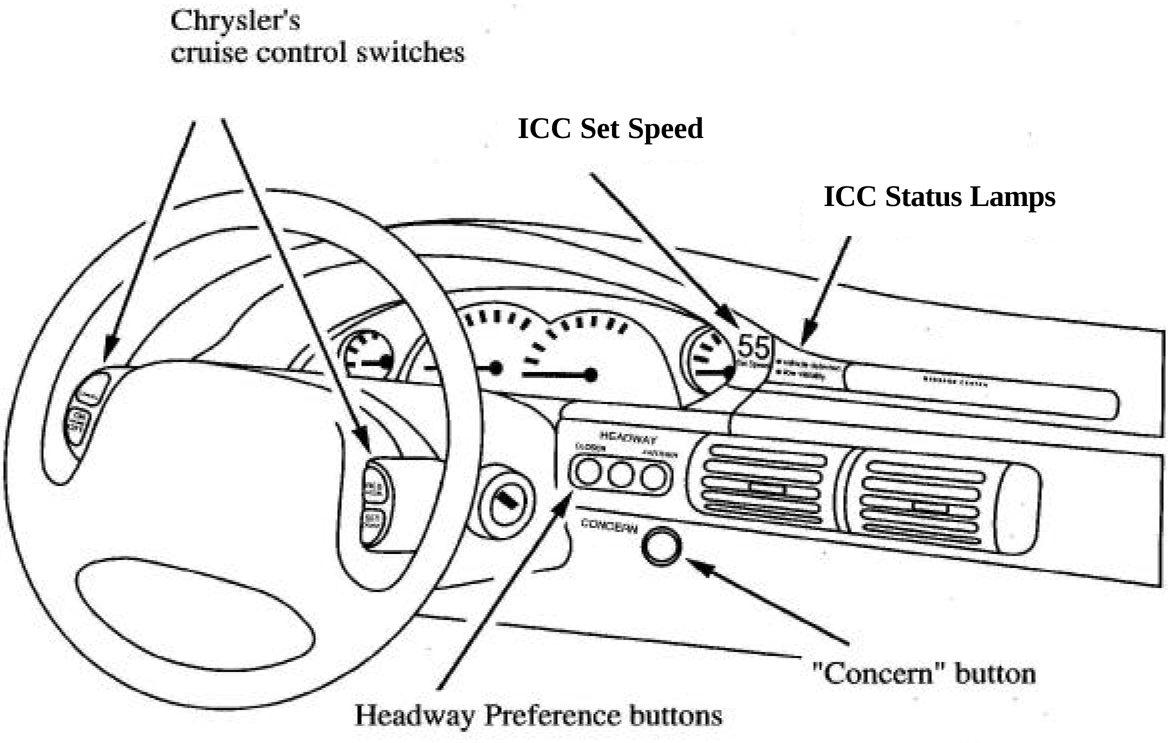


Adapted from UMTRI *Test Definition and Project* Plan(1996)

Figure 2-3 Range, Range Rate Illustration of ICC Controller Function

Figure 2-4 illustrates the ICC user interface in the Chrysler Concorde console. The steering wheel hub buttons: CANCEL, to left; ON/OFF, lower left; ACCelerate/RESume, upper right; and SET/COAST, lower right, were standard and located on the Concorde steering wheel. There was also a standard status lamp indicator on the dashboard to indicate when the cruise mode was engaged.

Four custom buttons and three custom indicators were unique to the ICC vehicles. To the right of the steering wheel stock were three buttons that provided the driver with three headway time (T_h) options: “closer”, a middle setting, and “farther”. These settings corresponded to 1.0,1.4, and 2.0 second headway times, respectively. The ICC set velocity was displayed numerically to the right of the standard instrument cluster. Two status lamps to the right of the set velocity display indicated “vehicle detected” — whether the ICC system was tracking another vehicle, and “low visibility” — whether atmospheric backscatter was preventing tracking. A CONCERN button was provided below the headway selection buttons. The CONCERN button supported field operational test data collection and was to be used to flag and record video on events that the driver thought the test and evaluation staff should examine.



From UMTRI *Test Definition and Project* Plan (February, 1996)

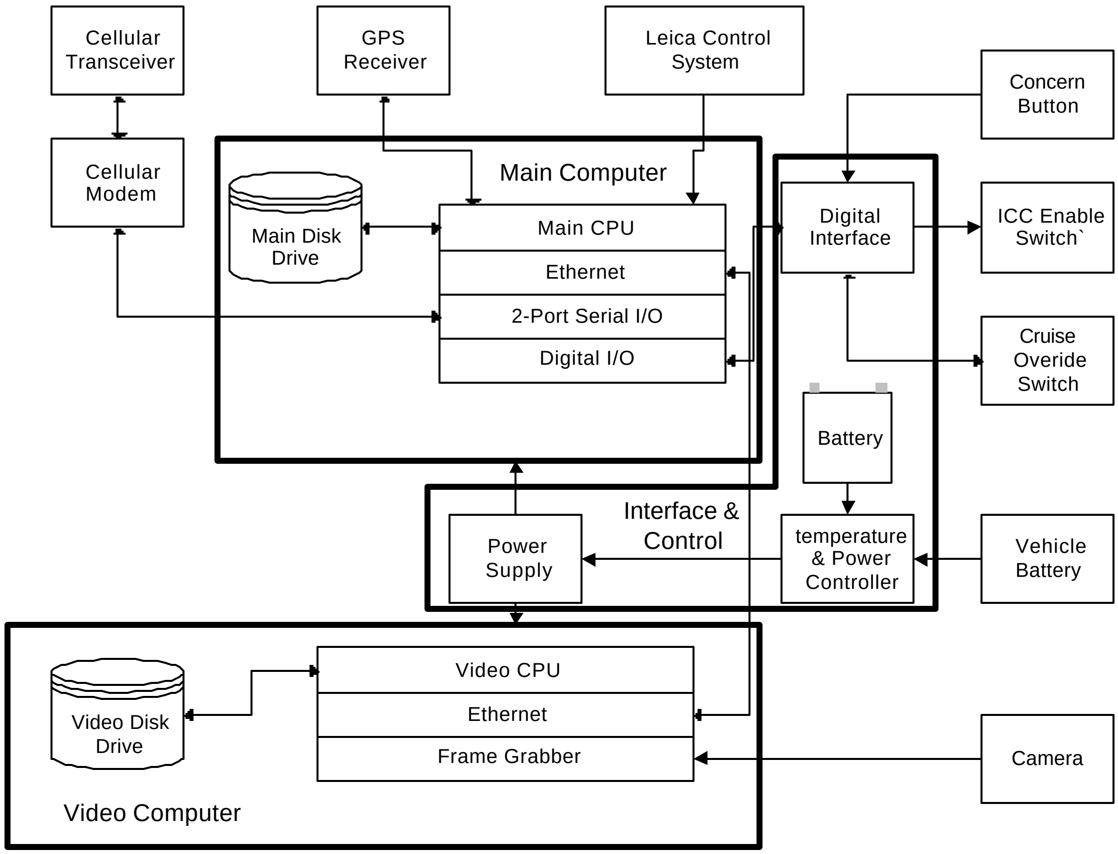
Figure 2-4 ICC User Interface

2.2 ICC Data Acquisition System

The ICC Field Operational Test resulted in extensive data collection. Sources of onboard data were:

- the driver interface,
- the Leica sensor, E-Box, and Controller,
- GPS, and
- a video camera.

Figure 2-5 depicts the architecture of the onboard data acquisition system. Two hard disks stored data. The main disk stored most of the system data. The video disk stored images of events captured by the video camera.



Adapted from UMTRI Test Definition and Project Plan(1996)

Figure 2-5 ICC System Data Acquisition Hardware Architecture.

2.2.1 Main Disk Data

UMTRI regularly downloaded summary data from the main disk via cellular modem linkage. The summary data was used by UMTRI to monitor system performance, to ensure that the vehicles were being used, and to evaluate the field operational test. The complete data set was downloaded each time a vehicle was returned to UMTRI. The main disk drive stored four file types:

- GPS files,
- time history files,
- trip log files, and
- event log files.

GPS Files. These files included data from the GPS receiver: time, latitude, longitude, altitude, etc. The sampling rate for GPS data was 0.5 hertz.

Time History Files. The bulk of the data used in the evaluation was stored in these files. A sample of the variables stored in these files is shown in Table 2-1.

Table 2-1 Selected Variables Captured in Time History Files by the Onboard Data Acquisition System

Name	Type	Description	Source	Sampling Rate	System Units
Date/Time	Double	Days since Dec 30 1899 +fraction of day	GPS & CPU		days
Range	Float	Distance to target	Leica	10 Hz	ft
RangeRate	Float	Rate of change of range	Leica	10 Hz	ft/sec
Velocity	Float	Vehicle velocity	Leica	10 Hz	ft/sec
VSet	Float	Cruise velocity set by driver	Leica	10 Hz	ft/sec
VCommand	Float	Velocity commanded by controller	Leica	10 Hz	ft/sec
Headway Time	Float	Selected headway time	Leica		sec
CurveRadius	Float	Curve radius	Leica	10 Hz	ft
Throttle	Float	Throttle percent	Leica	10 Hz	%
Backscatter	Float	Backscatter index (1 to 1023)	Leica		
Brake Active	Logical	True if brake pedal is pressed	Leica		
Target	Logical	True when tracking a target	Leica		
NewTarget	Logical	True for .3 sec with new target	Leica		
ValidTarget	Logical	Target and velocity filter	Leica		
ICC Mode	Integer	ICC control mode	Leica		

From UMTRI Test Definition and Project Plan(1996)

Trip Log Files. These files contained counts of certain events and other information useful for identifying the trip from which the count came. Events such as brake interventions in ICC operation, turning the ICC system on, and traveling at velocities greater than 80.5 km/h were counted.

Event Log Files. These files stored a chronological history of important, but irregularly occurring events such as button presses by the driver. Also stored in this file were events that triggered videos to be stored such as deceleration above a certain level or near encounters with other vehicles.

2.2.2 Video Disk Data

The videos from the camera, as opposed to events that triggered the video, were retained on the video disk drive. For each driver, approximately 200 thirty-second video events, and 420 two-second video events were triggered and stored. The videos consisted of 60-degree field-of-view, black and white images, captured at a rate of 5 frames per second. Each frame had a horizontal resolution of 512 pixels and a vertical resolution of 64 pixels.

Two classes of video information were recorded: episodes and exposures.

2.2.2.1 Episode Videos Episode videos were 30 seconds in length. Episode recordings were triggered by one of three events:

- brake interventions,
- near encounters, and
- CONCERN button presses.

Brake interventions. Brake interventions were recorded when the following three conditions occurred simultaneously: (1) the brake pedal was depressed, (2) velocity exceeded 64.4 km/h, and (3) average deceleration over 4 seconds exceeded 0.05 g. Videos for up to 50 of these events were saved for each of four conditions: (1) CCC available but CCC not engaged (i.e., manual driving, first week); (2) CCC engaged; (3) ICC available, but not engaged (i.e., manual driving, weeks 2-5); and (4) ICC engaged. When available storage space on the video disk was reached, the 20 highest priority events in each condition were retained. Priority was determined by the deceleration value. Higher decelerations were given higher priority. Fifteen seconds of the video that preceded and followed each brake intervention was saved.

Near encounters. Near encounters were recorded when an the average braking force of greater than 0.05 g would be required to avoid a time-headway of 0.3 seconds The velocity also had to be greater than 64.4 km/h. Videos for up to 50 of these events were saved for each of four conditions. These conditions were the same as those listed for brake interventions. When available storage space on the video disk was reached, the 20 highest priority events in each condition were retained. Priority was determined by the amount of g force required, with higher g's receiving higher priority. Fifteen seconds of the video that preceded and followed each near encounter was saved.

CONCERN button presses. When the CONCERN button was pressed, the video for the preceding 30 seconds was recorded to the video hard disk, and a CONCERN button press was logged in the event log. The last 50 CONCERN button presses were always retained.

2.2.2.2 Exposure Video Events Exposure videos were 2 seconds in length. Exposure recordings were triggered automatically every five minutes for the two-week drivers and every ten minutes for the five-week drivers. The primary purpose of the exposure videos was to provide a basis for obtaining information on roadway type, congestion, and weather.

2.3 ICC Sensor Performance

The ICC sensor system had two infrared laser emitters and two receivers. All four units were mounted above the front bumper in the grill area between the headlamps, approximately 0.6 meters above pavement level. One transmitter and associated receiver, together referred to as the sweep sensor, was mounted on the left (driver) side of the grill. The other transmitter and associated receiver, together referred to as the cut-in sensor, was mounted on the right (passenger) side of the grill.

2.3.1 ICC Sensor Field of View

The reported horizontal coverage area for the sensors (Fancher, Ervin, Sayer, Hagan, Bogard, Bareket, Mefford and Haugen, 1997) is depicted in Figure 2-6. The cut-in sensor had a range of 32 meters and a 7 degree field-of-view (FOV). As its name implies, the cut-in sensor was intended to detect vehicles pulling into the ICC vehicle's lane at close range. At closer ranges, the sweep sensor beam was too narrow to pick up objects not in the center of the lane.

The sweep sensor was intended to detect a preceding vehicle in the area ahead between 32 meters and 133 meters. The horizontal FOV of the sweep sensor was reported as 1.9 degrees, and the vertical FOV was reported as 3 degrees. Thus, at 133 meters the beam was 4.4 meters wide, horizontally. A typical freeway lane width is 3.65 meters. A gyro dynamically steered the sweep sensor in response to lateral motion of the ICC vehicle. The sensor was reported capable of steering 3 degrees in either direction for a total coverage area of approximately 8 degrees. The sweep was intended to assist the system in maintaining tracking through curves.

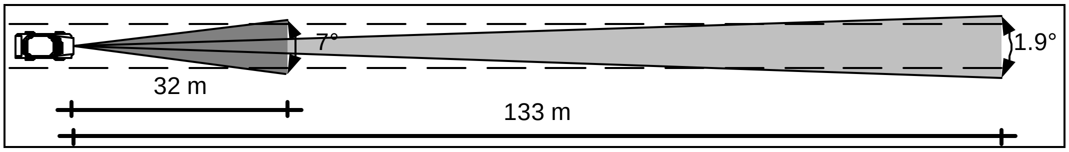


Figure 2.6 Reported Sensor Coverage Areas (approximately to scale)

The evaluation team attempted to verify the reported sensor FOV This was done by moving a 20 cm square plaque into and out of the sensor FOV while the vehicle was parked. A readout device, supplied by UMTRI, was used to monitor range to targets the system detected. The cut-in sensor was assessed by moving the plaque in and out of the field at a distance of 6 meters. The sweep sensor FOV was assessed at 34, 67 and 100 meters. The procedure was repeated five times, each, to detect the left, right, top, and bottom edges of the FOV The bottom edge of the FOV was measured by elevating the front wheels of the vehicle until the edge of the beam was detected, and using the elevation to determine the angle. The measured FOV results are shown in Table 2-2. Note that both sensors were tilted up somewhat. Comparison of the reported and measured horizontal FOV shows them to be very close. The differences are probably within the accuracy of the field measurement methodology. The measured vertical FOV of the cut-in sensor differed by several degrees from that reported by the development team (i.e., 3 degrees).

Table 2-2 Measured and Reported Field-of-View of the ICC Sensors

	Measured		Reported	
	Cut-in	*Sweep*	*Cut-in*	*Sweep*
Horizontal	7.1°	2.0°	7.0°	1.9°
Vertical	10.5°	4.0°	3.0°	3.0°
Vertical Tilt	3.3°	0.5°	na	na

Both the reported and measured FOV characteristics of the ICC system were felt to be adequate to reliably track targets over hills, dips, and curves found on freeways. The evaluation team did identify some curves on secondary roads on which the system momentarily lost track of a preceding vehicle. (This was also noticed during examination of some of the video episodes.) However, the acceleration characteristics of the vehicle, combined with momentary nature of these target loses, were such that the driver might not notice these target loses. Ramps onto and off of limited access roadways often have curves beyond the capability of the sensor system, and, in part, for this reason, FOT participants were instructed not to use the system on ramps.

The evaluation team also discovered that the ICC system did not perform well in snow because snow would accumulate on the bumper and sometimes generate false negatives as the snow scattered return signals from the lead vehicle before they reached the sensor. In other instances the snow on the bumper would generate false positives as it reflected signals directly back to the sensors. Because the ICC system was a prototype, it was decided not to test the system under snow conditions. Trips that were conducted under snow conditions were identified and removed from the analysis. The trips that were removed and the process for removing them are discussed in Appendix A, *Snow Trip Examination*.

Comparisons of actual distance to targets with distances reported by the system were made using both vehicles and reflective plaques as targets. A counting wheel was used to measure distances independent of the ICC system. The measurements were made while the ICC vehicle was parked. Measurements were taken at 6, 34, 67, and 100 meters. In no case was the difference between the ICC system distance estimate and the counting wheel estimate greater than 1 meter. At 6 and 34 meters, the ICC system and the counting wheel estimates were the same.

On the road, the ICC system detected targets out to 133 meters. However, stable acquisition of targets occurred around 100 meters. In the data record, as the ICC vehicle approached a slower moving vehicle, targets tended to appear and disappear on a deci-second basis until a range between 80 and 100 meters was attained. In an attempt to characterize this phenomenon, the targets were classified as “good” if they appeared in the data stream 5 or more deci-seconds, and their change in range between deci-seconds was less than 20 meters. Targets were classified as ephemeral, or short-lived, if they lasted less than 5 deci-seconds or their range changed by more than 20 meters between deci-seconds. Table 2-3 shows, for a sample driver, the number of freeway deci-seconds records classified as ephemeral. For the sample driver, out of 145,261 deci-second records (242.1 minutes of driving) recorded on freeways, when the system determined the range to be between 0 and 20 meters there were 35 records, or 0.024 percent or all records, that were classified as ephemeral.

Ephemeral records – records not marked as “good” – were excluded from most analyses in this report. It can be seen in Table 2-3 that this exclusionary filter affected very few deci-second records. Over 110 million deci-second records of vehicle state were recorded in the vehicles. Rather than incorporate all 110 million records in the evaluation database, which would have made analyses unwieldy, one record was selected to represent each second of driving. To accomplish this, every tenth record was sampled. However, in sampling there was a risk that a record that represented an ephemeral target would be selected to represent the entire second. Because some of the ephemeral targets were known to be “false targets”, e.g., vehicle in another lane, or roadside features such as guardrails, it was decided to exclude ephemeral targets from the reduced data set.

Table 2-3 Percent of “Ephemeral” Targets Recorded on Freeways for a Sample Driver

Range (m)		*Frequency Of Ephemeral Targets*	*Percent of Records*	*Cumulative Percent*
min (≥)	*max (<)*			
0	20	35	0.024%	0.024%
20	40	100	0.069%	0.093%
40	60	119	0.082%	0.175%
60	80	203	0.140%	0.315%
80	100	209	0.144%	0.458%
100	120	251	0.173%	0.631%
120	140	357	0.246%	0.877%
140	160	0	0.000%	0.877%

2.3.2 Retro-Reflectivity and Target Resolution

Tests were conducted to determine the minimum retro-reflectivity requirements of the system, and how the system behaved in the presence of multiple targets within its FOV.

2.3.2.1 Minimum Retro-Reflectivity Preliminary analysis indicated that the ICC system was very sensitive to the presence of preceding vehicles. This section quantifies this sensitivity and describes the method that was used.

A 3.8 cm by 5 cm plaque with the calibrated reflectance of 70 cd/lux/m^2 was mounted on a non-reflecting, matte black stand such that the plaque was elevated 0.6 m above the ground. From directly in front of the vehicle, the plaque was moved toward the sensor until the system reported the plaque's range, and then away from the sensor until the plaque's range was no longer reported. This procedure was repeated five times.

Detection of the plaque occurred at 11 meters. The amount of reflected infrared energy required for target detection was calculated as 3×10^{-6} of original intensity of IR sensor output. The calculation is given in Appendix B *Calculation of Minimum Retro-Reflectivity for Target Detection.*

2.3.2.2 Multiple Target Resolution To determine how the system would behave when two targets were present in its FOV, tests were conducted by placing a smaller target near the sensor and moving a larger distal target toward the sensor until the system reported the range to the distal target. The smaller, near target was a 5 cm by 5 cm plaque with a retro-reflectance of 70 cd/lux/m^2. The larger target was a 20 cm by 20 cm plaque, also with a retro-reflectance of 70 cd/lux/m^2. The smaller target was placed on the longitudinal axis in front of the ICC vehicle at distances of 11, 34, and 67 meters such that its reflecting surface was normal to the direction of the sensor. The larger plaque was placed slightly off axis (such that the smaller plaque did not shadow it) at a farther distance. The headway distance reported by the ICC system was noted. If the system reported the range to the smaller plaque, the larger plaque was moved toward the ICC vehicle in one-meter increments until the range to the distal target was reported. Similarly, if the range to the distal target was initially reported, the distal target was moved farther away, in one meter increments, until the proximal target was reported. Moving the distal plaque in the alternating direction was continued until 5 target switches had been obtained at each proximal target distance.

The results of the multiple target testing are shown in Table 2-4. When the proximal target was at 11 meters, within the 32 meter range of the cut-in sensor, the system tracked the distal target if the distal target reflected 3 or more times the energy reflected by the proximal target. When the proximal target was at 34 or 67 meters, in the coverage area of the sweep sensor, the system tracked the distal target if the distal target reflected 10 or more times the energy reflected by the proximal target. This is explained further with the aid of Figure 2-7. The ratio of the target area divided by the square of the range was computed for both the near and distal targets. In the cut-in sensor range, the distal target would be detected if its ratio exceeded 3 times the ratio for the proximal target. In the range of the sweep sensor, the distal target was detected instead of the proximal target if the distal target's ratio exceed 10 times the ratio of the proximal target.

Table 2-4 Multiple Target Testing

Measure:	**Proximal target/Distal target**		
Reflector Distances	11 m/ target switch occurred @ 25 m	34 m/ target switch occurred @ 43 m	67 m/ target switch occurred @ 81 m
Solid Angle Ratios	1:3	1:10	1:10

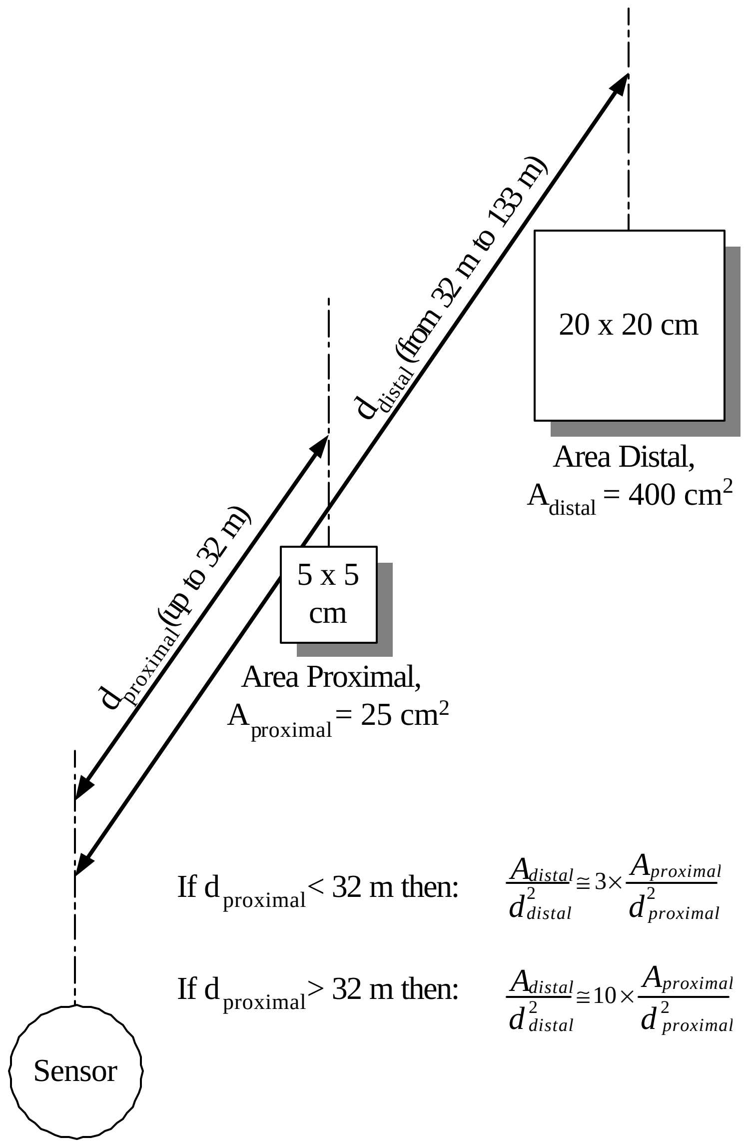


Figure 2-7 Determining Ratio of Energy Required for Distal Target to Override Proximal Target

The energy ratios required for far objects to be detected when near objects (vehicles) are present in the lane make it unlikely that automobiles could be lost in reflections from trucks that precede them, or that motorcycles could be concealed in the reflections from cars that precede them. It is possible that the ICC system might fail to detect a small motorcycle that closely follows a large truck. This possibility was not empirically investigated. However, in at least one case during the field operational test, a motorcycle was successfully detected and tracked. This was noted during analysis of the episode videos. Furthermore, the evaluators did field test the ability of the system to detect a motorcycle following another passenger car.

On-road testing was conducted with a Ford Taurus and Harley Davidson FLHTC motorcycle, respectively, representing distal large and proximal small targets. In general, the system tracked the motorcycle well, particularly when the ICC vehicle approached the motorcycle traveling in the same lane. There were cases when the motorcycle was not detected. These cases involved either the motorcycle cutting into the ICC vehicle's lane, or the ICC vehicle changing to the motorcycle's lane. The system's failure to detect the motorcycle was never caused by the presence of the larger distal target. Rather, there were blind spots in which the motorcycle was not detected regardless of background reflections.

The areas where motorcycle detection failed are illustrated in Figure 2-8. Areas C and D are not likely to be of concern, because there are redundant alternative means of detecting the motorcycle. First, the driver of the ICC vehicle is always responsible for monitoring the roadway. However, even if the ICC driver did not initially respond to a slower moving motorcycle in this area, the cut-in sensor would eventually pick up the motorcycle. The result of closing on a slower moving motorcycle traveling in the left or right side of a lane was a brief acceleration when the motorcycle came into areas *C* and *D*, followed by deceleration as the motorcycle came within 32 m. This situation required driver intervention if the difference in motorcycle velocity and desired set velocity were large. Areas *A* and *B* are within 15 meters of the ICC vehicle. These are in areas in which the ICC driver should be visually attending to the motorcycle even before a lane change occurs. Furthermore, any vehicle intruding only as far as any of the four blind spots would not be detected by the system. In the judgement of the evaluators, the system does not pose any special hazard to motorcycles. This is because: (1) the scenarios where the system fails to detect motorcycles are those in which the ICC user normally expects to intervene regardless of ICC performance, and (2) any vehicle that intruded into the same space would pose the same risk.

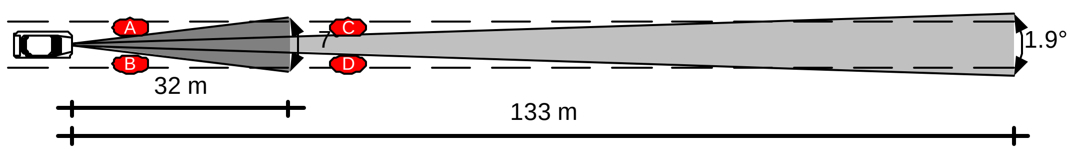


Figure 2-8 Areas in Lane Where Motorcycle can be Within Range but Outside Coverage Area

2.4 ICC Driver Interface Characteristics

ICC specific driver interface elements consisted of three headway selection buttons, a set velocity indicator, and indicator lamps identifying low visibility and vehicle detected. The remainder of the ICC interface relied on existing conventional cruise control buttons that retained the same functions as for conventional cruise control. The headway selection buttons offered a choice of three headway settings: 1, 1.4, and 2 seconds However, the time-headway settings were not numerically labeled. Rather, the button for 1-second headway was labeled "closer" and the 2-second headway button was labeled "farther." The 1.4-second headway button was unlabeled, but positioned between the other two buttons. These buttons were located to the right of the steering wheel, on the dashboard, between the steering column and the radio. The buttons and set velocity indicator were illuminated to a level equivalent to the rest of the instrument panel. The button luminance ranged from 3 to 7 cd/m^2.

All the controls were within reach for virtually all drivers, as the driver's seat was electronically adjustable over a wide range, the steering wheel had an adjustable tilt, and the conventional cruise control buttons were mounted on the steering wheel hub.

When drivers completed participation in the test, they filled out a questionnaire about their experience with the ICC system. All 108 drivers completed the questionnaire. The questionnaire did not specifically address the acceptability of the ICC driver interface. However, one question asked whether the "system components" were distracting, and offered the indicator lamps and headway selection buttons as examples of system components. Possible responses were on a scale from 1 to 7, where 1 was labeled "very distracting" and 7 was labeled "not at all distracting." Only 12 percent of the 108 respondents indicated that they thought the components were distracting, 10 percent were neutral, and 78 percent gave a rating greater than 4. Of those providing a rating greater than 4, 48 percent selected the 7 rating. Thus, questionnaire ratings suggest that the majority of respondents perceived the interface positively.

In comments on the questionnaire, some respondents did offer suggestions for improving the driver interface. Table 2-5 provides a summary of comments offered by 2 or more respondents. The most frequent comment, offered by 6 individuals, suggests that users found the low visibility warning buzzer annoying.

Table 2-5 ICC User Interface Improvements Suggested by Two or More Questionnaire Respondents

Comment	Frequency
Make the low visibility sensor less sensitive or remove buzzer	6
Add brightness control for buttons and display	5
Provide a warning light when below selected headway	2
Display current headway	2
Offer shorter headway selection	2
Offer longer headway selection	2
Offer continuous dial headway selection	2

Several recommendations for improvements to the ICC controls and displays came from the focus groups. Roughly one-fourth of focus group participants suggested that the displays be integrated into the dashboard instrument cluster. This recommendation was not unexpected as placement of the prototype displays was driven by the desire to avoid occluding existing displays and was not part of the original vehicle design. Similarly, about one-fifth of the participants recommended integrating the ICC controls onto the steering wheel hub where the CCC controls are located. Several also suggested illuminating the controls on the steering wheel hub. Most of the participants who recommended changes in the controls and displays were from among the group of participants who claimed to be prior users of conventional cruise control.

2.5 Characterization of Integrated ICC System and Vehicle Performance

The evaluators undertook a number of pilot tests on the highway before and during the conduct of the FOT. The purpose of this pilot testing was to collect vehicle and system performance data under controlled conditions. The resultant data were used to characterize system performance and develop models that could be used to analyze FOT data that were not collected under controlled conditions. In the following sections we present some of these data and briefly describe the models that were based on them.

2.5.1 ICC System Performance for Four Driving Scenarios

In this section four scenarios are depicted using data recorded by the ICC system during controlled pilot testing:

- following another vehicle that is traveling at a constant velocity,
- following another vehicle that begins a rapid acceleration,
- following another vehicle that begins a rapid deceleration, and
- approaching a slower moving vehicle that is traveling at a constant velocity.

Whereas the ICC FOT generated a tremendous amount of data under all of the above scenarios, characterization of the specific scenario at any given time had to be inferred solely from the sensor data. Although episode videos were collected when the ICC vehicle braked above a certain level or had near encounters with preceding vehicles, video was not normally collected for typical driving conditions. To aid in interpreting the field data, the evaluators produced the above scenarios, and others, and simultaneously recorded a continuous video. The sample data presented here are intended to provide an understanding of how the ICC system performed on a second-by-second basis under typical driving conditions. In the chapters that follow, summary statistics such as average headway and average velocity will be presented. Some of the later findings will be related directly back to performance in these typical scenarios.

2.5.1.1 ICC Vehicle Following Another Vehicle at Constant Velocity Figure 2-9 shows data recorded by the ICC system while it followed a confederate (controlled preceding) vehicle that had its cruise control set at 78 km/h. The range variable is the distance, in meters, between the front bumper of the ICC vehicle and the rear of the preceding vehicle. Range rate (Rdot) is rate of change in range between the two vehicles in meters per second, and is negative when the distance between the two vehicles is closing. Percent of throttle and Rdot are plotted against the right ordinate, all other measures are plotted against the left ordinate.

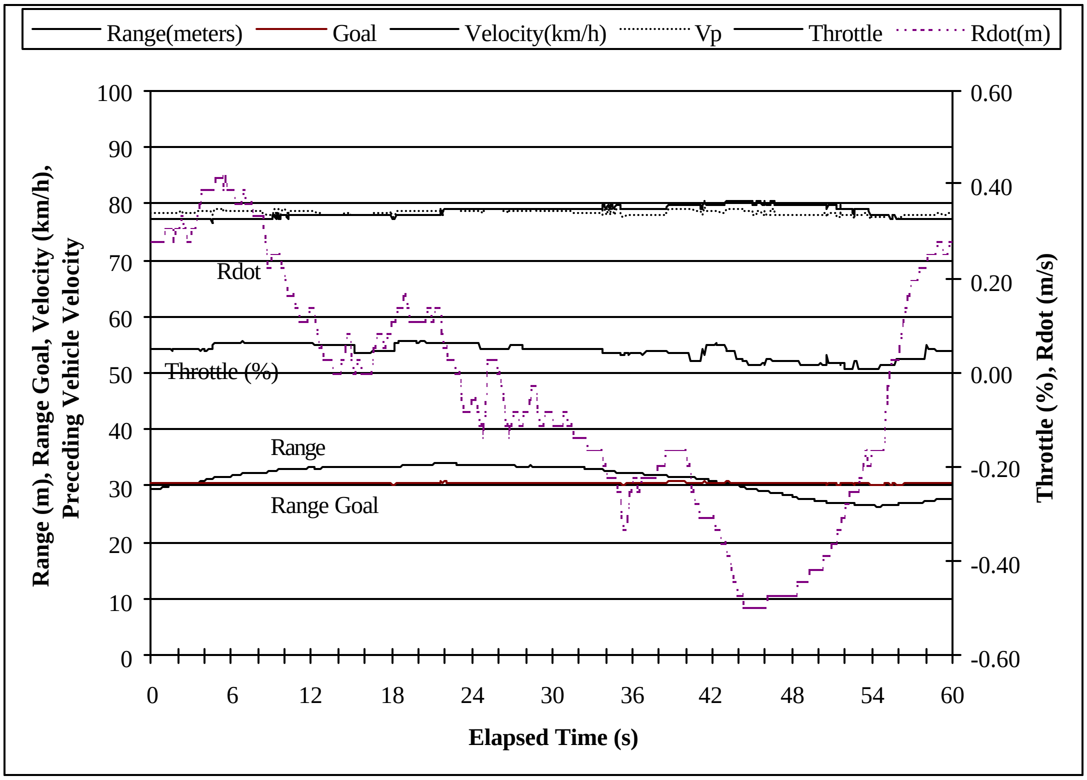


Figure 2-9 System Performance Variables for ICC Vehicle with 1.4 Second Time-Headway Selected Following a Constant Velocity Vehicle

The ICC vehicle had a much higher set velocity (96 km/h) and had been following the confederate vehicle for some time. The ICC time-headway setting was 1.4 seconds. The “range goal” shown in Figure 2-9 was computed from the preceding vehicle’s velocity, as reported by the ICC system, e.g., goal equals preceding vehicle velocity (meters per second) times 1.4 seconds. It can be seen that the ICC vehicle was less aggressive in accelerating to close the range gap in seconds 4 through 42 than it was to extend the gap in seconds 42 through 60. This asymmetry, which favors longer than selected average headway, resulted in a mean time-headway of 1.43 seconds for the charted interval. The plot of the preceding vehicle’s velocity can be seen as a line briefly deviating above and below the ICC vehicle’s velocity plot.

2.5.1.2 ICC Vehicle Following Another Vehicle that Rapidly Accelerates Figure 2-10 shows the system performance variables for the case where the preceding vehicle accelerates away from the ICC vehicle. Again, the ICC vehicle had a high set velocity and had been following the preceding vehicle for some time. The ICC time-headway setting was 1.0 second. At about the 10th second into the scenario in Figure 2-10, the confederate vehicle began to accelerate from 60 km/h to a target velocity of 94 km/h. The ICC vehicle accelerated at an average rate of about .040 g and reached the lead vehicle’s velocity at about the 34th second. The ICC vehicle then decelerated at a rate of about .036 g to regain the selected time-headway at about the 55th second. Although the ICC vehicle slightly overshot the desired headway between seconds 55 and 80, the average time-headway for the 90-second scenario was 1.4 seconds. Even though the maximum acceleration and deceleration rates of the ICC vehicle were nearly equal, as in the previous scenario, the ICC system tended to operate in a way that resulted in an average time-headway that was longer, and perhaps safer, then the selected time-headway.

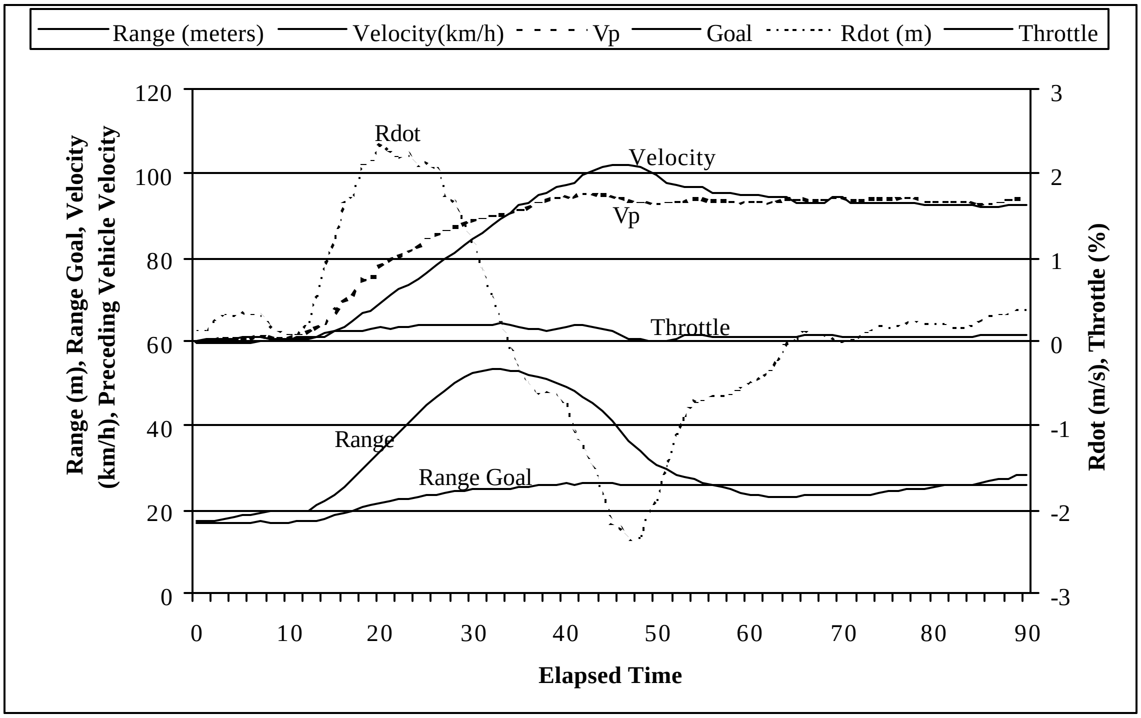


Figure 2-10 System Performance Variables for ICC Vehicle with 1.0 Second Time-Headway Selected Following a Vehicle Accelerating from 60 to 94 km/h

2.5.1.3 ICC Vehicle Following a Decelerating Vehicle Figure 2-11 shows the system performance variables for a scenario in which the preceding vehicle decelerates from 96 km/h to approximately 63 km/h. The ICC time-headway setting was 1.0 second. The maximum deceleration of the lead vehicle was 0.053 g, and the average lead vehicle deceleration during the first 10 seconds of the scenario was 0.031 g. The lead vehicle had just begun its deceleration in the seconds that preceded second 0 in the figure, and the vehicles had not reached steady state following before the end of the 60-second interval. However, it can be seen that the lead vehicle deceleration came close to requiring greater deceleration than the ICC vehicle could achieve. The maximum deceleration rate of the ICC vehicle during the scenario was about .64 g. The ICC vehicle could achieve about .05 g deceleration without a downshift, and about .07 g with a downshift. The minimum range was 4.5 m and the minimum time-headway was 0.26 second. The average time-headway during the displayed portion of the scenario was 0.68 second, and the maximum time-headway was 1.10 seconds. The maximum time-headway occurred at second 0, and the minimum occurred at second 29. It is arguable whether a 4.5 m headway is comfortable at 62 km/h (39 mi/h). However, because no braking was required, this scenario illustrates a case where the system approached its limits in providing a convenience that relieves the driver from the necessity to intervene in cruise control operation. It also illustrates a case where a substantially lower time-headway (0.26 second) than the set headway (1.0 second) can be achieved while driving in the ICC mode.

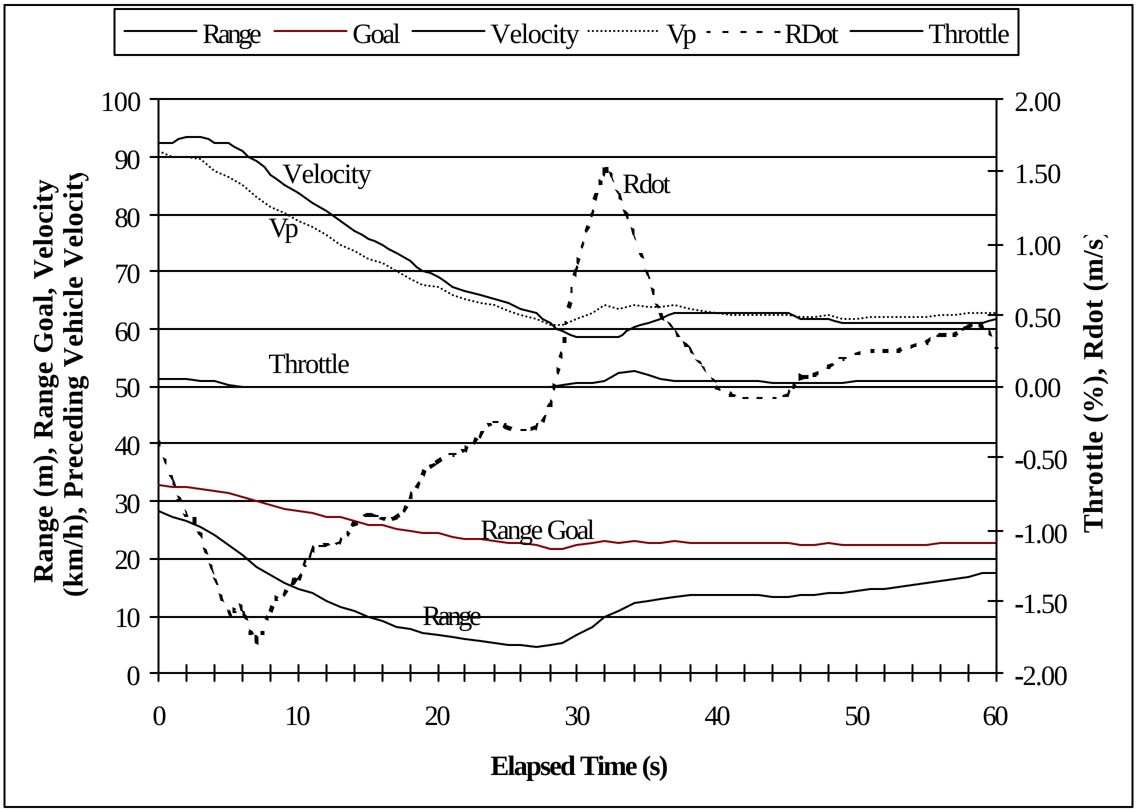


Figure 2-11 System Performance Variables for ICC Vehicle with 1.0 Second Time-Headway Following a Vehicle Decelerating from 96 to 63 km/h

2.5.1.4 ICC Vehicle Approaching a Slower Vehicle Figure 2-12 shows the performance variables when the ICC vehicle was initially traveling at 86 km/h and approached a vehicle cruising at 52 km/h. The ICC vehicle had a 1.0-second time-headway selected. At 0 seconds the ICC system has not acquired the preceding vehicle. Once the target was acquired, the throttle went to zero and, between seconds 2 and 3, the ICC vehicle began to decelerate. The minimum range, about 4m at second 25, was less than most drivers would allow, but was within the capabilities of the system. The maximum deceleration was 0.049 g. The average time-headway for the portion of the scenario depicted in Figure 2-12 was 1.64 seconds, the minimum was 0.25 seconds and the initial time-headway at the instant the target was acquired was 4.93 seconds.

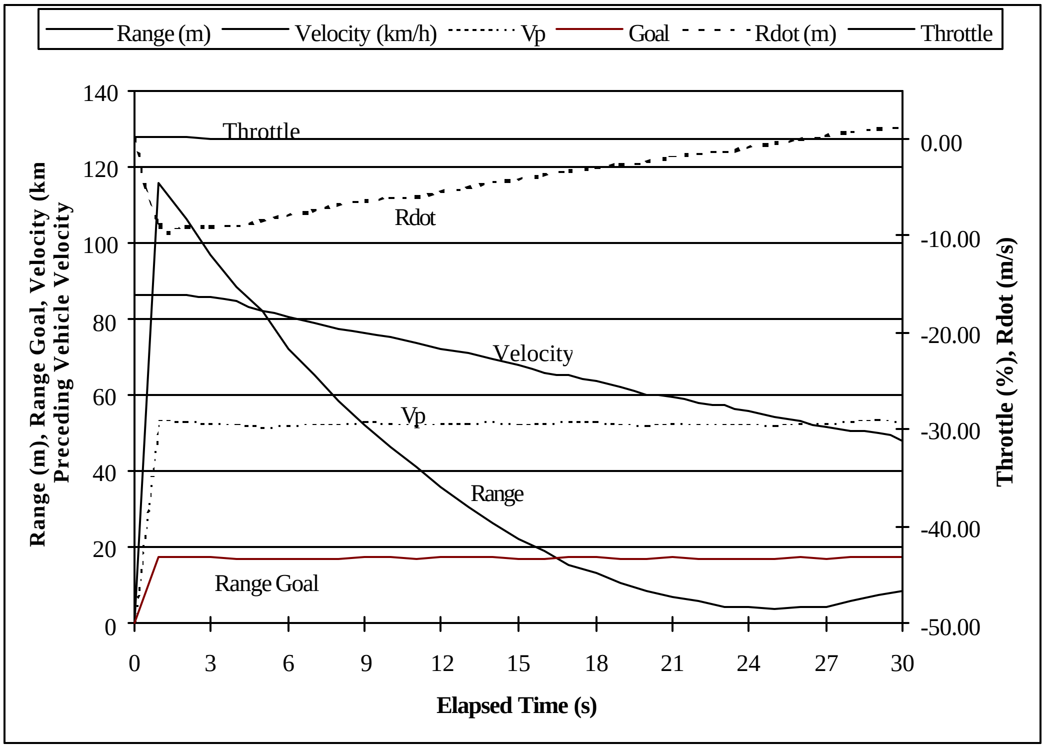


Figure 2-12 System Performance Variables for ICC Vehicle with 1.0 Second Time-Headway as it Approached a Slower Constant-Velocity Vehicle

2.5.2 ICC System Performance in Contrast to Manual Driving

Figure 2-13 shows a plot of velocity versus range samples taken at 2-second intervals for 15 to 20 minutes of freeway driving with each of the ICC headway settings. The data were collected by selecting a relatively high set velocity, and then following another vehicle through normal (low density) traffic. The best fitting linear regression of range on velocity has also been plotted for each of the time-headway settings. It can be seen that the ICC system maintains a fairly tight linear relationship between range and velocity throughout the cruising range. The slopes of the linear regressions relating velocity to range correspond to the inverse of average headway time (Vp=R/Th). Using the linear regressions, the calculated time-headways are 1.00, 1.42, and 2.02 seconds for the 1.00, 1.40, and 2.00-second headway settings, respectively. Based on these results, the ICC system does a remarkably good job of achieving, on average, the desired time-headways when tracking other vehicles.

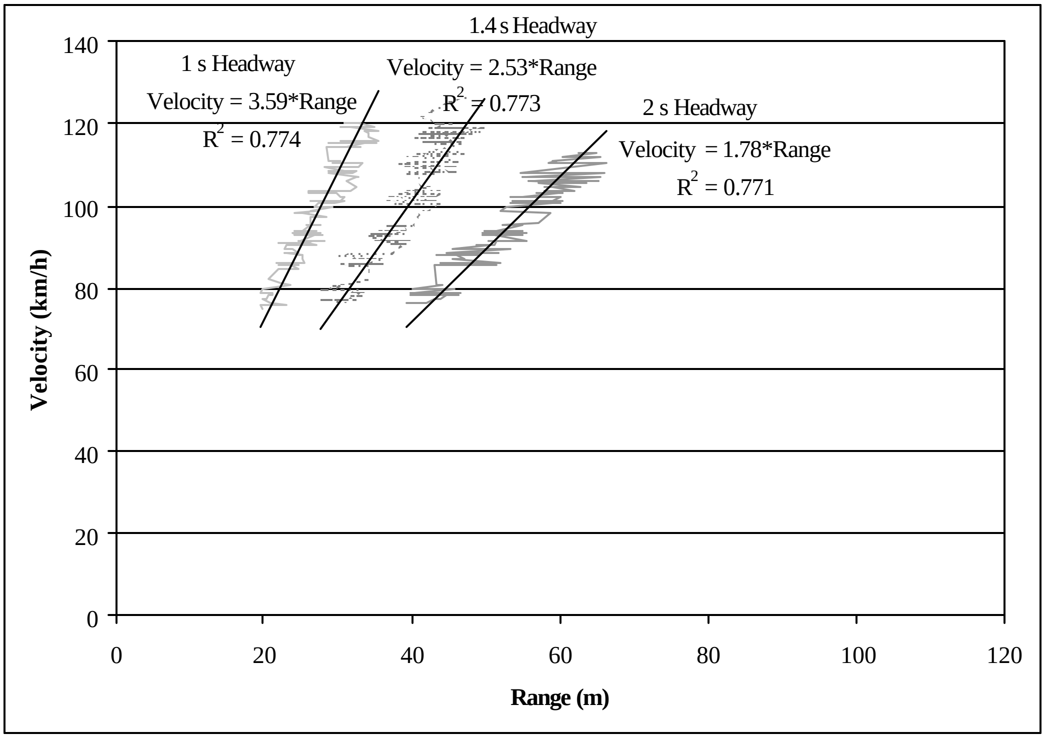


Figure 2-13 Typical ICC Velocity-Range Relationship for Freeway Driving

Figure 2-14 shows the cumulative time-headway distributions for the three time-headway settings based on the same data presented in Figure 2-13. As Figure 2-14 shows, the distributions are very narrow with means about equal to the three time-headway settings.

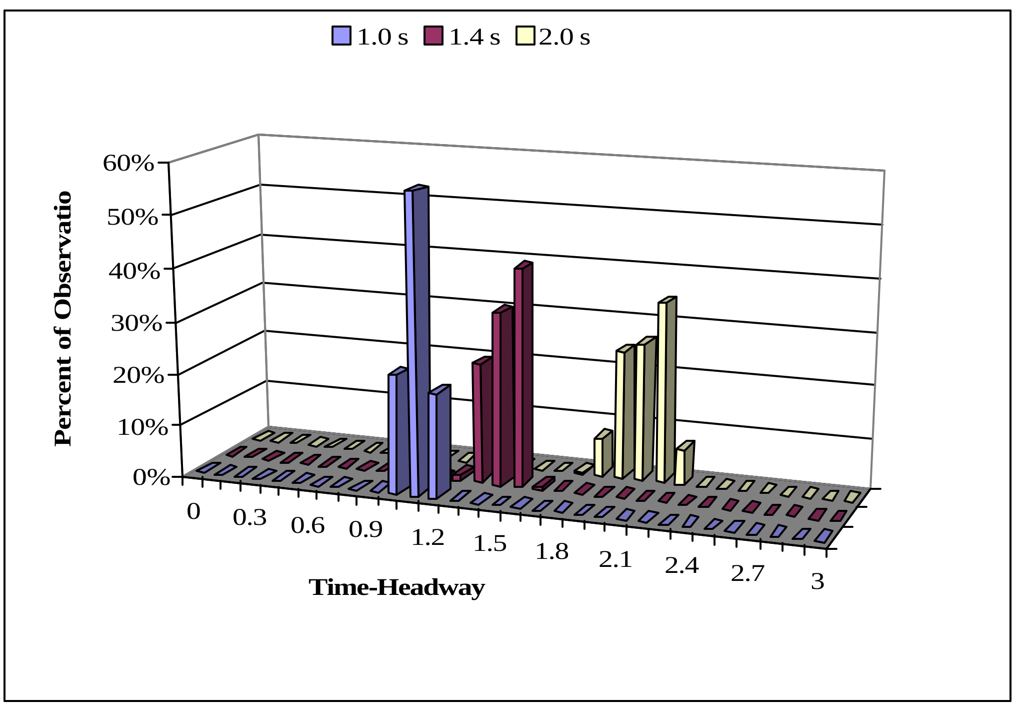


Figure 2-14 Distribution of Time-Headway for Each of Three Time-Headway Settings

Figure 2-15 shows velocity – range relationships from three members of the evaluation team who were instructed to follow traffic as they normally would without use of the ICC system. In contrast to the ICC system, the velocity-range relationships from the evaluation team, for normal, manual driving shows considerably more variation. For these cases of manual driving, the velocity-range relationship tended to be curvilinear. These data came from a trip on the same freeways at the same time of day, as the data shown in Figure 2-13. The three drivers were selected, *a priori* (that is before the drives), for their driving styles: one tended to be very "aggressive" in that he preferred to drive fast and with very close ranges. Another tended to drive more slowly than average, and to maintain longer ranges. The third was thought to have an intermediate style.

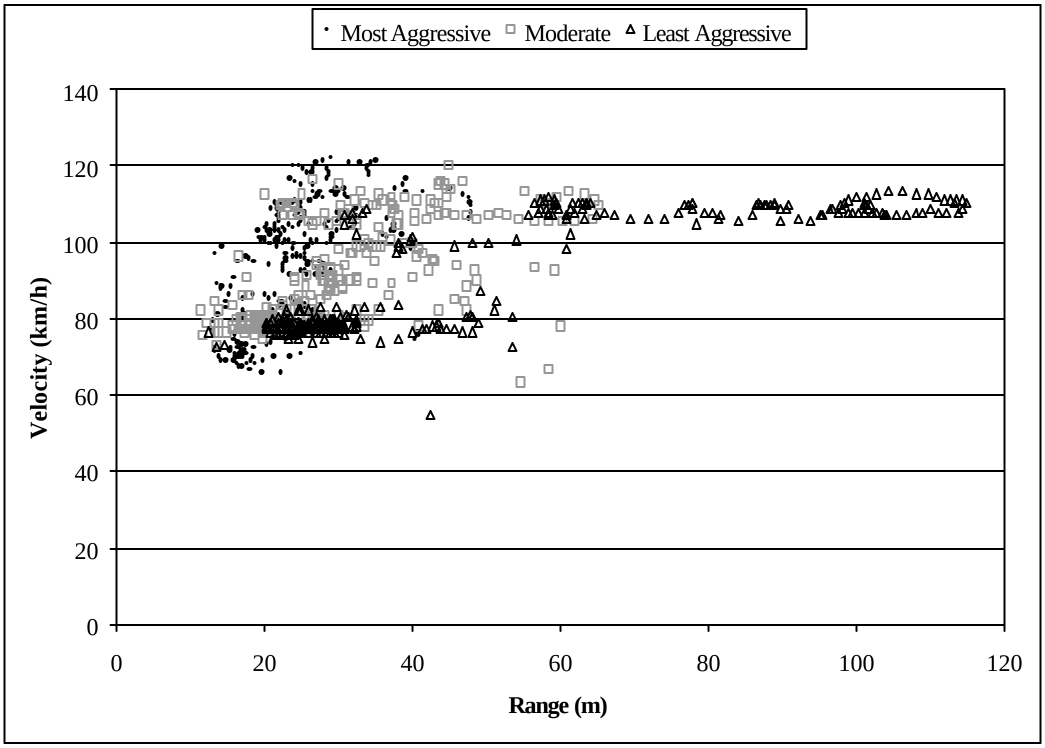


Figure 2-15 Manual Driving Velocity-Range Relationship From Three Individuals with Different Driving Styles

Figure 2-16 shows the cumulative time-headway distributions for the three manual driving styles based on the same data presented in Figure 2-15. As Figure 2-16 shows, the distributions are much broader than the ICC driving distributions shown in Figure 2-14. The means of the three driving style distributions are about 0.88 seconds for the most aggressive driver, 1.12 seconds for the moderately aggressive driver, and 1.41 seconds for the least aggressive driver.

On average, the driver thought to be more aggressive maintained shorter ranges and time-headways, and the driver thought be less aggressive maintained the longest ranges and time-headways. However, it can be seen from Figures 2-15 and 2-16 that at low velocities (less than 80km/h) all three maintained similar ranges and time-headways. If these drivers are representative of the general driving population, then it appears that ICC might result in longer ranges and/or time-headways at lower freeway velocities, as well as less variable gaps and, dependent on driving style, shorter ranges and/or headways at higher velocities. However, these drivers were instructed when to use, or not use the ICC system. The FOT data reflect when and where drivers elected to use ICC, and are a better source for safety-outcome and -impact data. The data presented in this section are intended primarily to show how the system performed under specific conditions. More detailed analyses of the effects of ICC system use on time-headway, range, velocity, and other driving parameters, based on the FOT data, are presented in subsequent chapters.

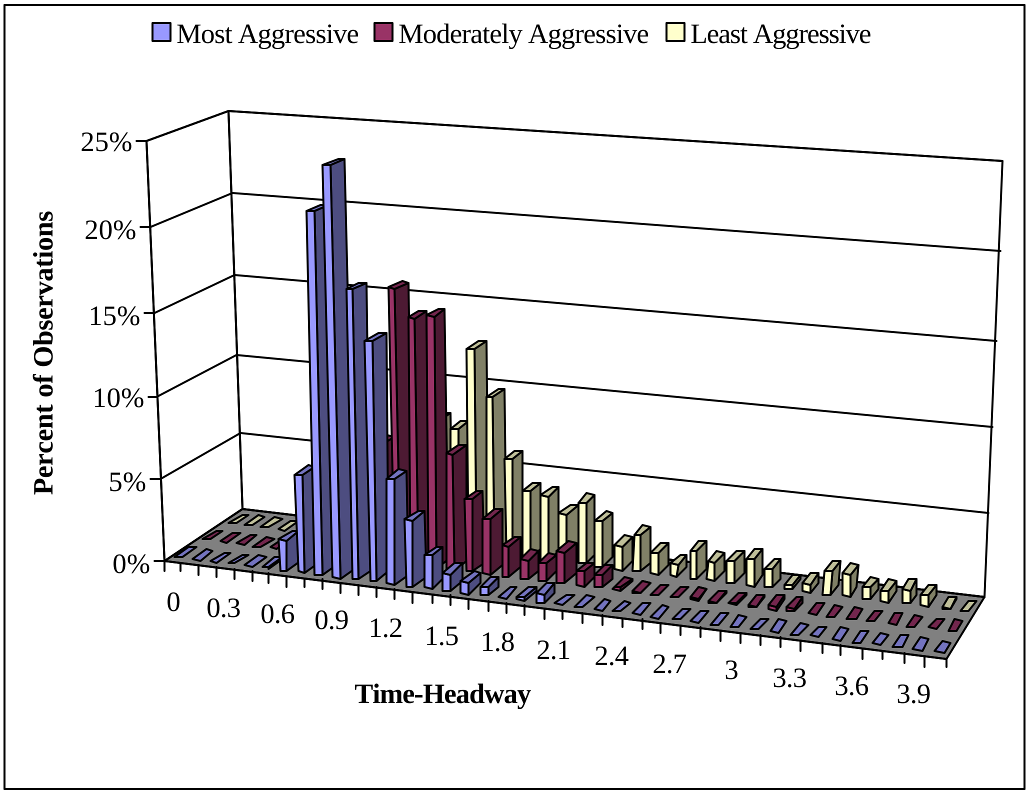


Figure 2-16 Distribution of Time-Headway from Three Pilot-Test Drivers Who Used Manual Control of Cruise Velocity

2.6 Evaluation Tool Development

This section briefly discusses the development and validation of tools that were developed to assist in performing the evaluation. Many, but not all, of the tools relied heavily on data collected during the pilot-test phase of the evaluation.

2.6.1 Characterization of Vehicle Driving States and Transitions Based on Data from Sensor

In later portions of this report, analyses are performed that break driving down into component *states* and *transitions.* A *safety analysis framework* is developed in Section 3 in terms of the states and transitions so that the effects of ICC on safety can be related to specific driving states and scenarios. Use of the *safety analysis framework* allows a clear description of where the safety analysis of this study is focused relative to all driving and where future analysis may be conducted. In this section we briefly define the driving states and transitions and describe how they were derived from the data collected in the vehicles. For a complete description of the nationale, calculations, and validation of the driving state algorithms see Appendix C, *Driving State Identification Tool.*

The driving states were intended to be exhaustive, that is, all driving could be classified into one of four driving states.

Driving States. Four basic states were defined:

- following,
- closing,
- separating, and
- cruising.

Following was defined as driving behind another vehicle within sensor range, where the preceding vehicle velocity was within ± 1.5 m/s (5 ft/s) of the velocity of the host (ICC) vehicle.

Closing was defined as driving behind another vehicle within sensor range, where the preceding vehicle was traveling at a velocity at least 1.5 m/s slower than the host vehicle.

Separating was defined as driving behind another vehicle within sensor range, where the preceding vehicle was traveling at a velocity at least 1.5 m/s faster than the host vehicle.

Cruising was defined as driving with no preceding vehicle within sensor range. For purposes of providing reliable classification of the cruising state, the sensor range was limited to that corresponding to a 2.4-second headway. For example, if a vehicle was detected at a time-headway of 2.5 seconds, it was classified as cruising.

Closing and Separating were further subdivided into closing or separating *slowly* or *rapidly*. If the difference in velocities of the host and preceding vehicle was greater than 6.1 m/s (20 ft/s) then they were classified as closing or separating *rapidly*, otherwise they were classified as closing or separating *slowly*.

Following, Closing and Separating were also subdivided according to time-headway. Time-headway less than or equal to 0.8 seconds was classified as *close*. Time-headway greater than 0.8 seconds, but less than or equal to 1.6 seconds, was classified as *middle.* Time-headway greater than 1.6 seconds, but less than or equal to 2.4 seconds, was classified as *far*.

Transitions. In addition to the driving states, driving *transitions* were defined that could account for changes in driving state. From an algorithmic standpoint, transitions were instantaneous events that had no duration, and always were associated with a new driving state.

Four transitions were defined:

- target acquisition,
- target switch,
- target drop, and

- acceleration.

A *target acquisition* occurred when a preceding vehicle was present and the previous state had been cruising.

A *target switch* describes a transition from following one preceding vehicle to following another. The change in preceding vehicles was defined algorithmically as an instantaneous (one deci-second to the next) change in range to the preceding vehicle greater than or equal to 1.5 m (5 ft), or an instantaneous change in preceding velocity greater than or equal to 7.6 m/s (25.0 ft/s). It should be noted that with this definition, if the criteria are not met, it does not mean that there was no switch, but rather one could not be determined positively. The implications are discussed later in this report.

A *target drop* was defined as a switch to cruising from one of the other driving states.

An *acceleration* transition, designated as *a* elsewhere in this report, was defined as the relative acceleration between the target and host vehicles leading to a change in state.

Target acquisitions, drops, and switches were subdivided into *active* and *passive.* An active transition was defined as a transition that resulted from a lane movement by the ICC vehicle. Transitions that were not classified as active were classified as passive, and were presumed to have resulted because of the actions of other drivers.

The following section describes how a lane movement by the ICC vehicle was identified in the data stream.

2.6.2 Identification of Lane Movements

Where a target acquisition, switch, or loss was identified in the data stream, a classification was also made as to whether the change in target was caused by the lane movement of the ICC vehicle, or the result of actions of the preceding vehicles. When a target acquisition, switch, or drop was associated with the lane movement of the ICC-equipped vehicle the change was termed *active*, i.e., the result of an act of the host vehicle driver. When the ICC equipped vehicle was determined not to have a lane movement, the change in target was termed *passive*, i.e., not the result of an action by the host vehicle driver.

During pilot testing, the evaluation team conducted several test drives in which lane movements of varying severity were performed for later laboratory analysis. In the laboratory, the recorded lane movements in the digital data, specifically the degree of curvature variable, were identified manually, by comparison with continuous video records and CONCERN button presses used to mark lane movements.

An elegant, but reliable algorithm was then developed to identify lane movements in the ICC system data stream. The algorithm was validated against data not used in algorithm development. Appendix D, *Development of a Lane Movement Algorithm* provides a complete description of the algorithm and the development process. A brief description is given next.

A plot of a prototypical lane movement is depicted in Figure 2-17 on a grid where the abscissa is time in deci-seconds and the ordinate is degree of curvature (Fancher, et al, 1997).

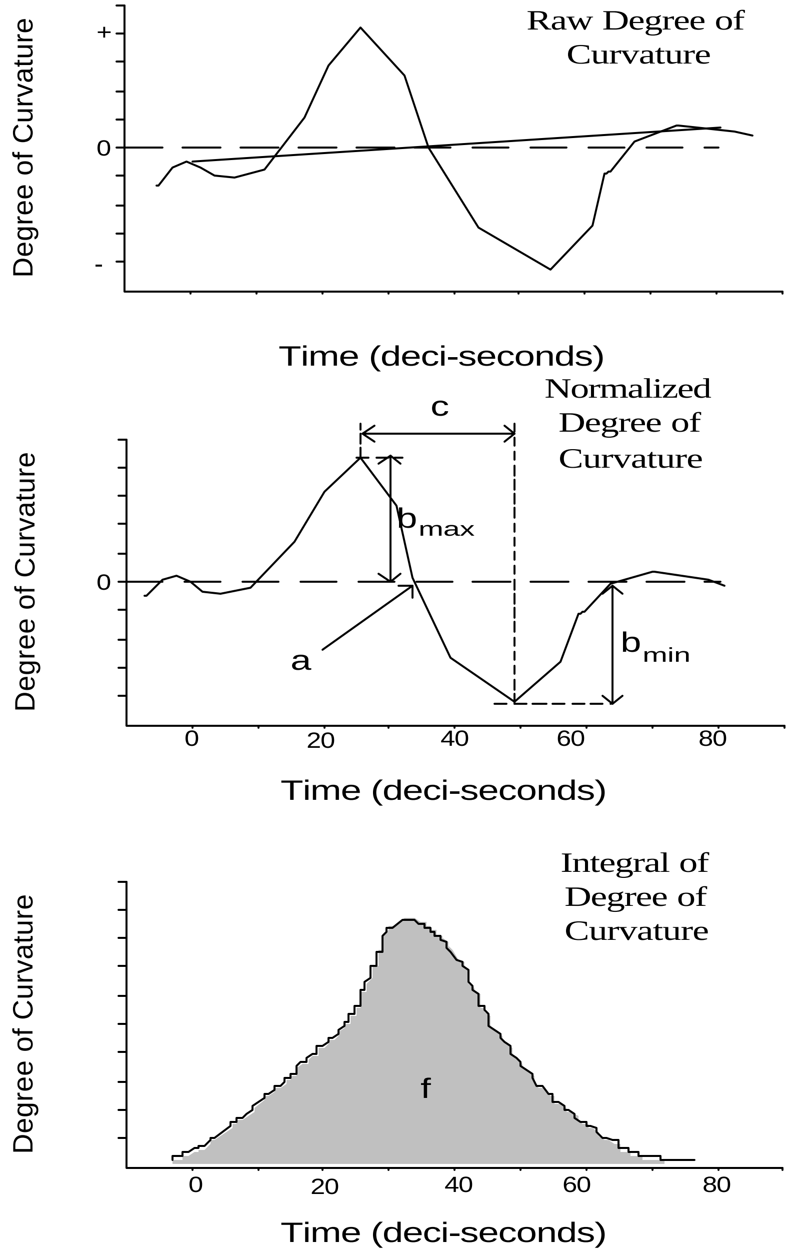


Figure 2-17 Elements of Lane Movement Identification Algorithm

The steps to determining whether a lane movement occurred were as follows:

1. for each 8-second interval where velocity was greater than 40.3 km/h, determine the slope of the line that connects the degree of curvature for the first deci-second record in the interval (the record at 0) with the degree of curvature at the 80th record,

2. linearly transform each of the 80 points such that the slope between the first and last points is zero,

3. determine the values of the parameters bmax, bmin, c, a, and f that are depicted in Figure 2-17, and

4. compare parameters against criteria, shown in Table 2-6, for a lane movement.

Table 2-6 Criteria for Parameters Used to Identify Lane Movements.

Parameter	Description	Minimum Value	Maximum Value
f	area under curve	16	200
a	inflection point	0.1 sec	5.0 sec
$\lvert b_{max}\rvert$ and $\lvert b_{min}\rvert$	Amplitude	0.6	5.0
c	time interval between peaks	1.5 sec	n/a

The algorithm was applied to every set of 8 seconds in the data stream in 1-second steps. The algorithm had a low false alarm rate, but tended to miss lane movements that involved more than one lane or were contiguous with exit or entrance ramps on limited access roads.

2.6.3 Calibration of Fuel Consumption and Emissions Effects

One of the evaluation objectives was to assess the impacts of ICC on fuel consumption and emissions. Because the ICC data acquisition system did not record fuel consumption, it was necessary to estimate fuel consumption. Similarly, no means was available to measure vehicle emissions in the field, so it was necessary to estimate emissions.

The model used to estimate fuel and emissions was developed by the Center for Transportation Research at the Virginia Polytechnic Institute and State University (VPI) (Ahn, et al., 1998). VPI developed the model by fitting third order polynomials to data supplied by Oak Ridge National Laboratories (ORNL) (West, et al., 1997). Appendix E *Fuel Consumption and Emissions Estimation* summarizes the approach to constructing computational algorithms and queries of the FOT database.

The ORNL data was produced by first recording engine loading on the highway, and then replicating those loadings using a laboratory dynamometer. Fuel consumption and emissions were measured in the laboratory, simulating highway conditions for velocities between 0 and 110 ft/s in one ft/s increments, and accelerations from –5 ft/s^2 through 12 ft/s^2, in 1 ft/s^2 increments. ORNL performed this procedure for eight different vehicles. The vehicle tested that was most similar to the Chrysler Concorde used in the ICC FOT was an 1994 Oldsmobile 88. The Oldsmobile 88 was equipped with a 170-horsepower 3.8-liter, six-cylinder engine. The Concorde had a 214-horsepower, 3.5-liter, six-cylinder engine.

The form of the equation fit by VPI to the Oak Ridge data was the same for fuel consumption, HCO, CO, and NO:

$$ln(Y)=a+bA+cA^2+dA^3+eS+fS^2+gS^3+hAS+iAS^2+jAS^3+kA^2S+lA^2S^2+mA^2S^3+nA^3S+oA^3S^2+pA^3S^3$$

where the equation symbols are defined in Table 2-7.

Table 2-7 Definition of Symbols in Fuel Consumption and Emissions Model

Symbol	*Value*
Y	Fuel consumption (liters/second) or emission rates (milligrams/second)
a	Intercept
b,c,…,p	Regression coefficients
A	Acceleration (ft/s^2)
S	Velocity (ft/s)
ln	Natural log, base “e” (e = 2.718281828 ...)

The coefficients of these equations for the Oldsmobile 88 are shown in Table 2-8.

Table 2-8 Fuel Consumption and Emissions Model Parameters.

Parameters	*Fuel Consumption*	*Hydro Carbon Emissions*	*Carbon Monoxide Emissions*	*Nitrogen Oxide Emissions*
a	-7.5474000000	-0.9213460000	0.9944280000	-3.6453100000
b	0.1873190000	0.0500794000	0.1801960000	0.4122050000
c	0.0316184000	0.0325467000	0.0370812000	0.0893588000
d	-0.0025869100	-0.0009235180	-0.0017690900	-0.0083433700
e	0.0246331000	0.0146511000	0.0457495000	0.1166630000
f	-0.0002673000	-0.0002347900	-0.0007079830	-0.0013377000
g	0.0000020294	0.0000044247	0.0000072996	0.0000081175
h	0.0037867500	0.0149929000	0.0152469000	0.0178212000
i	0.0000320880	-0.0001638290	-0.0002061070	0.0000163313
j	-0.0000002552	0.0000006016	0.0000010308	-0.0000010757
k	-0.0011520900	-0.0013172400	-0.0014625700	-0.0025063100
l	0.0000308215	0.0000735484	0.0000862032	0.0000567589
m	-0.0000002291	-0.0000005011	-0.0000006236	-0.0000005377
n	0.0000391402	-0.0001522230	-0.0001638210	0.0002827000
o	-0.0000013617	0.0000011040	0.0000022414	-0.0000119278
p	-0.0000000087	0.0000000071	-0.0000000100	0.0000000280

The ORNL/VPI fuel consumption and emissions model was selected for use because it is sensitive to acceleration differences that may exist between CCC, ICC, and manual driving. The evaluation team developed another model specifically for the ICC FOT, but this model used only velocity and three percentages of throttle settings (< 20 percent, 20 to 30 percent, and above 30 percent) as inputs. The ICC specific model was accurate in predicting overall fuel consumption of the Chrysler Concorde. However, as shown in Figures 2-9 through 2-12, the Concorde throttle rarely exceeded 20 percent.

2.6.4 GIS Map Matching

In the FOT, participants were free to drive wherever they wanted. Although each car captured video images of the forward roadway every 5 or 10 minutes, these video images proved inadequate for the purpose of classifying the roadways on which participants drove. Classification of roadways from the video was labor intensive and was also incomplete; several roads could be traversed in 10 minutes, and average trip length was not much greater than 10 minutes. And although the vehicle database contained Global Positioning System (GPS) coordinates, there was no Geographical Information System (GIS) associated with the coordinates. Thus, the data gathered during the FOT was inadequate, by itself, to enable the evaluation team to identify the road types that participants were using. As crash rates vary with road type, and velocities can vary widely across road types, it was deemed critical that the evaluation team be able to identify where, as well as when, participants chose to use cruise control.

To this end a GIS database for 11 counties in southeastern Michigan that the test drivers were most likely to drive in, was purchased from Etak[1], and custom software was developed to match roads in the GIS database to GPS coordinates in the ICC field data. Appendix F describes the *Development of the GIS/GPS Map Matching Tool*.

A map of the GIS coverage area is shown in Figure 2-18.

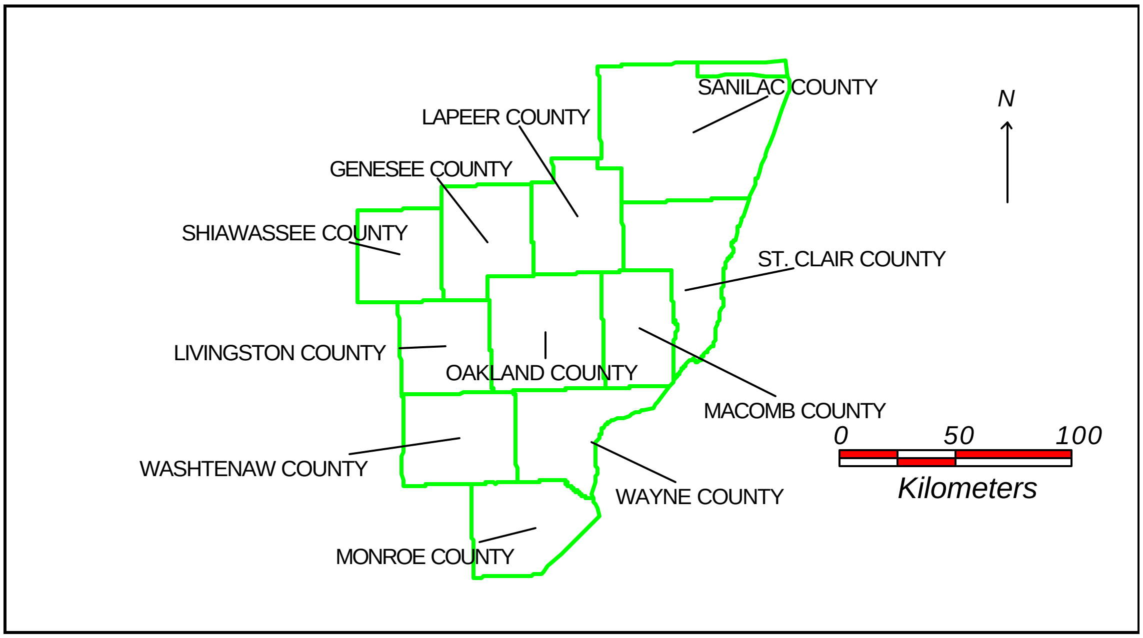


Figure 2-18 GIS Database Coverage Area

Prior to purchasing the database and developing the custom software, pilot tests were conducted to evaluate the quality of the GPS coordinates, and the variation in the quality between vehicles. The GPS data was found to be accurate and consistent. Furthermore, in trips through metropolitan Detroit, where buildings, bridges, and other obstructions formed an environment hostile to GPS signals, there were seldom gaps of more than 2 seconds without accurate updates, whether the travel was on freeways, or arterials. Figure 2-19 shows the GPS coordinates for pilot data from the same car, obtained on three different days, where the same ramp between I-275 and I-95 was negotiated. Consistency between different cars traveling at approximately the same time was far better than that obtained between days (represented in Figure 2-19). Deliberate er-

[1] Etak®, Inc., 1605 Adams Drive, Menlo Park, CA 94025

rors entered into the GPS signal by the US military (selective availability) appear to have been the largest source of signal error.

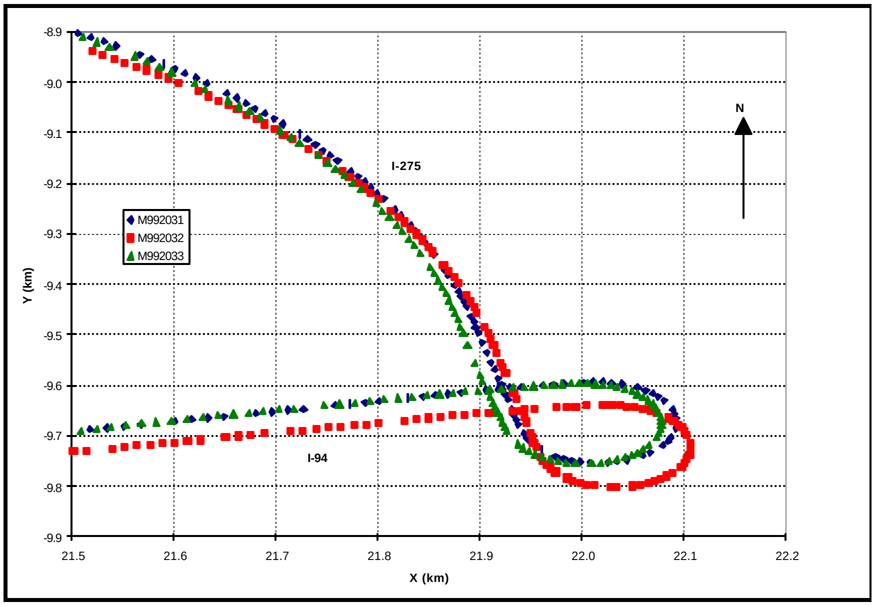


Figure 2-19 Consistency over Time for GPS Data on a Typical Freeway Route

Because the accuracy of the GPS coordinates was limited to about 30 meters, and because the map database may also have errors, matching of GPS coordinates with the GIS database had to allow for this imprecision, especially where roads crossed, or ran parallel to each other. The map matching software was subject to the following rules:

- where two roads were too close together to be distinguished, the higher class roadway (e.g., freeways are higher class than arterials) was selected,
- when a vehicle had been identified as being on a particular roadway, and a new set of coordinates matched that roadway and another, a bias towards the current road was carried for 8 seconds (if two roads remained equally probable for more than 8 seconds, then the higher-class roadway was selected), and
- where the road class changed from, or to, a freeway, the preceding 400 meters were classified as ramp.

Pilot test data were used to validate the model. A summary of the validation results is shown in Table 2-9. The final test results listed in the table were intended as a worst-case test of the algorithm; an arterial frontage road that was only a few meters from a freeway. In addition to identifying roads by class (i.e., high velocity ramp, freeway, state highway, arterial, collector, light duty, alley or unpaved, unknown, and low velocity ramp), population density, and road name were also classified.

Table 2-9 Summary of Map Matching Validation

Actual Road Type	*Percent of Distance Classified*	*Percent of Incorrect Road Identification*
Rural Arterial	100.0%	0.0%
Urban Arterial	99.4%	3.38%
Urban Freeway	99.4%	0.98%
Mixed Urban High Density	99.2%	3.08%
Freeway and Parallel Arterial	100.0%	20.6%

2.6.5 Congestion Model

The congestion model was developed so that ICC performance and utilization could be related to the prevailing level of traffic. The traffic engineering community describes the quality of traffic flow on any given roadway element in terms of a measure called the *level of service* (LOS). This measure is based on a six-level letter scale from LOS A to F. LOS A represents the best quality of flow. LOS D represents relatively crowded roadway conditions. LOS E describes the nature of operations when the roadway is operating near capacity. LOS F represents congested traffic flow. In most situations, LOS is related to the relative volume of traffic being carried by a roadway element and hence the level of congestion experienced. Thus, LOS A occurs at relatively low volumes with no congestion, LOS C or D occurs at moderate volumes and LOS F occurs at high volumes with severe congestion. *Roadway elements* are defined in terms similar to the roadway classes used in the ICC FOT. These elements include freeways, such as the *ICC* Interstate class, urban arterial streets included in the ICC arterial roadway classification, and rural multilane and two lane highways. Other roadway classes include ramps, collectors and local streets.

The *Highway Capacity Manual* (1997) describes techniques and standards for assessing level of service for different roadway classes. For freeways and multilane highways, LOS is assessed in terms of the *density* of traffic flow. Because it was not feasible to measure density for each roadway segment on each ICC FOT trip, an approximation method was required to quantify traffic density. This method relied on traffic flow data readily available from the ICC database. That is, the database provided instantaneous measures of velocity, acceleration and range to the preceding vehicle. Traffic density can be quantified using a velocity-density relationship or by taking the inverse of the space headway between vehicles.

A velocity-density relationship was derived as part of the pilot-test. Traffic flow, velocity and density data were obtained using video-imaging technology. The Autoscope™ machine vision system[2] was used for data collection on six freeway sites and one arterial site primarily in southeastern Michigan. Traffic data from these sites was used to develop a set of equations that relate velocity to density for each of the three primary roadway classes in the ICC database. Figure 2-20 shows the velocity-density curves that were developed.

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[2] Econolite Control Products, Inc., 3360 E. La Palma Ave., Anaheim, CA 92806.

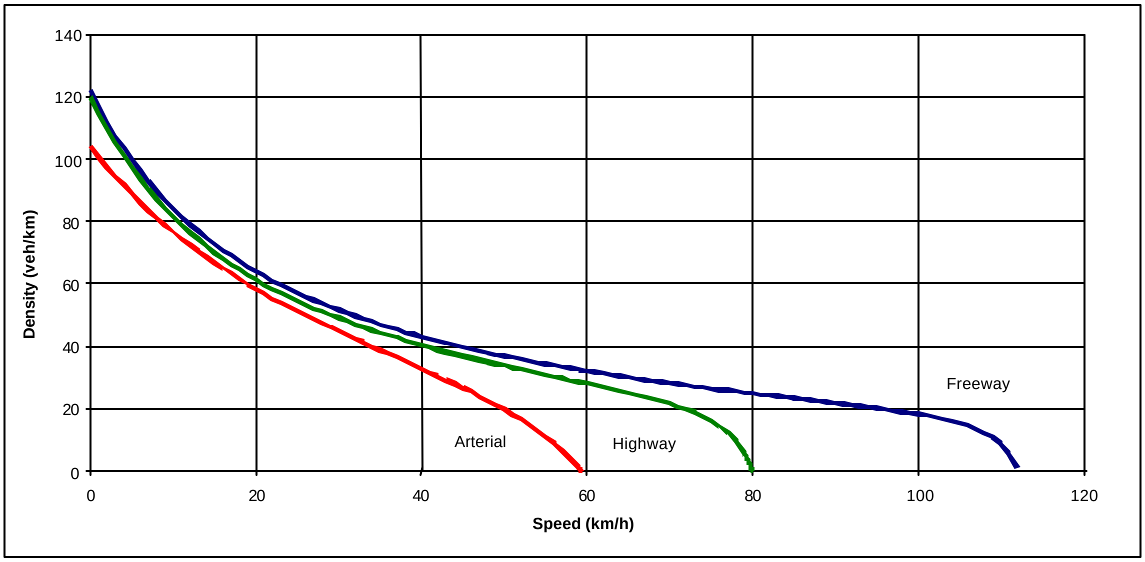

Figure 2-20 Derived Velocity Density Relationship for Three Roadway Types

A special curve form used by Van Aerde and Rakha (1996) was used to develop a model with the desired characteristics and boundary conditions. The mathematical form of the model and a definition of model coefficients are shown below. Table 2-10 summarizes the model coefficients used for each roadway class.

$$d = \frac{1}{c_1 + \frac{c_2}{s_f - s} + c_3 s}$$

where:

d = density (veh/km) or the inverse of the vehicle distance headway (km/veh)
s = velocity (km/h)
s_f = free velocity (km/h)
c_1 = fixed distance headway constant (km/veh)
c_2 = first variable headway constant (km^2/veh-h)
c_3 = second variable distance headway constant (h/veh).

Table 2-10 Density-Velocity Model Coefficients by ICC Roadway Class

	c_1	c_2	c_3	$s_{f\ (km/h)}$
Freeway	0.00353026	0.53066876	0.00030832	122.5
Highway	0.00533333	0.24000000	0.00023333	80
Arterial	0.00544531	0.19410714	0.00032181	57.2

The level of service experienced during travel was estimated as a function of the density of traffic flow and road class during each second of travel. LOS was only estimated when the vehicle acceleration rate was less than |±0.4| g (since the speed density relationships apply to steady-state traffic conditions in the model), was traveling more than 17 km/h, and was on a roadway classified as one of the three specified. This density was estimated as the lower value of the density predicted from the velocity-density equation, or the density predicted from the inverse of the space headway. The space headway was estimated as the range to the preceding vehicle plus a vehicle length factor of 5.1 meters (16.7 ft). The minimum value of density obtained from these two methods was used to determine the level of service using four ranges: A-B, C-D, E or F. The breakpoint boundaries for each level of service range are summarized in Table 2-11.

Table 2-11 Density-Level of Service Breakpoints as a Function of Road Class (veh/km)

Level of Service	*A-B*	*C-D*	*E*	*F*
Freeways	<10	10-20	20-27	>27
Other Roadway Classes	<7	7-12	12-17	>17

Pilot test data were used to validate the model. A complete description of the congestion model, including the validation results, is given in Appendix G, *Development of a Congestion Model*.

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3. Safety Effects of the ICC System

3.1 Introduction

This section presents the methodology and results with respect to evaluating the safety effects of the ICC system. The safety analysis reported herein is placed in the context of a s*afety analysis framework*. This *safety analysis framework* is defined in terms of driving states and transitions. These driving states and transitions encompass all driving situations. They include those that are perhaps most relevant to the ICC safety evaluation, namely, longitudinal-type interactions with a lead vehicle. The *safety analysis framework* thus allows a reference to be made to relevant driving situations and a logical path to be followed in conducting a comprehensive evaluation. The *safety analysis framework* also serves as an aid in the integration of the various safety surrogate measures.

The organization of the safety analysis is represented pictorially in Figure 3-1. In terms of results, overall usage data for the cruise control modes are presented first. Usage examines where and under what conditions ICC participants drove, and where and under what conditions they used the ICC system. Driving state and transition data are presented next. The usage, driving state, and transition patterns have a strong influence on driving safety, and also provide a useful means for describing the conditions examined under the safety evaluation.

With an understanding of where and under what conditions the ICC participants drove, safety-related data are then presented. The data are expressed first relative to overall driving behavior in terms of basic safety performance measures. The data are next presented relative to behavior in safety-critical situations in terms of safety-critical performance measures. This chapter ends with a review and assessment of driver perceptions of safety and an estimate of widespread safety benefits.

Most of the driving with the cruise control modes was on freeways and arterials, during light and moderate traffic conditions, and while cruising (no lead vehicle present, or lead vehicle present but substantially ahead of the host vehicle) or following another vehicle. Hence the focus of the evaluation is in these areas where sufficient data were available to perform a meaningful analysis. The drivers' behavior is characterized in terms of the basic safety performance measures: headway, velocity, acceleration, braking frequency, braking force, and driver response time.

Occasionally, drivers encountered safety-critical situations. These are expressed as closings and pre-crash scenarios. During these situations, their behavior is characterized in terms of the basic safety performance measures as well as close calls, safety boundary crossings (a new measure defined and described below), and closing rates. Sufficient data were not always available to determine statistically-significant findings in these situations. Nevertheless, the available data were examined, and the trends are indicated.

Throughout the analysis the focus is on ICC, and the behavior of drivers using ICC relative to driving under similar situations and conditions with manual control. As a secondary consideration, behavior relative to driving with CCC is also examined. The

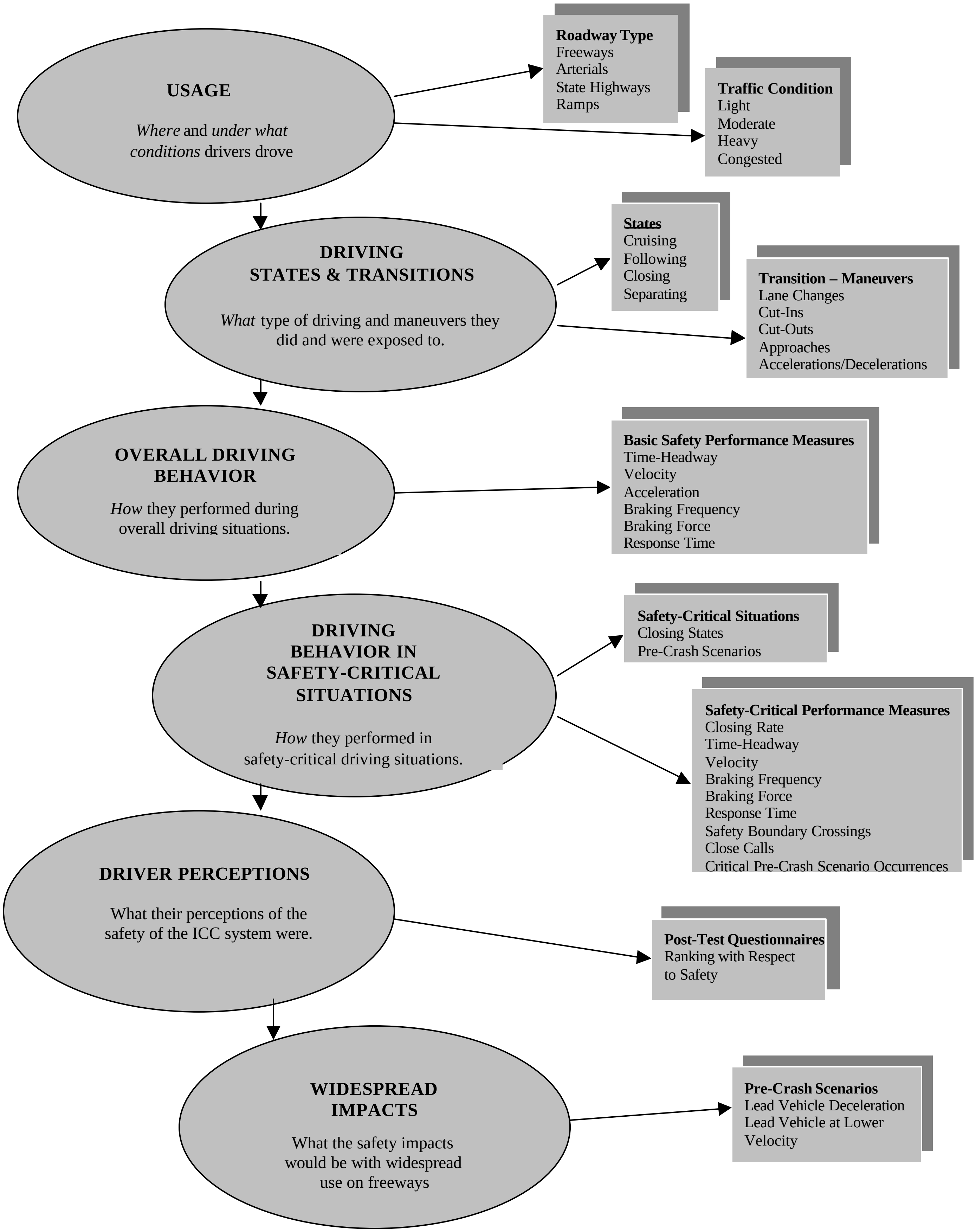

Figure 3-1 Safety Analysis Organization

results in comparison to both manual driving and driving with CCC provided two separate baselines for representing outcomes relative to situations and conditions with which most drivers are familiar, and sometimes served as bounds for the ICC performance measures.

3.2 Objectives

The safety evaluation objectives addressed in this study include the following:

- determine whether drivers drive more or less safely with the ICC system than without it in ways related to the system,
- determine whether drivers perceive a safety benefit from use of the ICC system, and
- assess whether widespread use of the ICC system would affect highway safety.

Questions and issues associated with these objectives, as described in Section 1.3, form the basis of the subsections below under the safety analysis results.

3.3 Safety Analysis Framework

This section describes the *safety analysis framework*. All analyses with respect to the specific safety surrogates and measures of performance including state space boundaries and pre-crash scenarios, described below, are referenced to this *safety analysis framework*.

Table 3-1 summarizes the *safety analysis framework* in terms of driving states and transitions. The driving states and transitions were defined in Section 2.6.1 and were derived from raw sensor data as described in Appendices C and D.

Table 3-1 Safety Analysis Framework

Driving States To → From ↓	*closing*	*following*	*separating*	*cruising*
	Transitions			
closing	switch	switch / *a*	switch / *a*	drop
following	switch / *a*	switch	switch / *a*	drop
separating	switch / *a*	switch / *a*	switch	drop
cruising	acquire	acquire	acquire	ALM

Note: All transitions are active or passive movements except for ALM

ALM – active lane movement (no lead vehicle present)

a – acceleration/deceleration

The driving states are listed in the left column and the top row. The driving states are mutually exclusive and a driver must be in one of these states at all times. A driving state was assigned to every deci-second of driving. The possible transitions from one state to another are indicated by the shaded cells. Transitions were assigned to account for changes in state and were treated as momentary events without a calculated duration. Transitions could occur without a change in state, e.g., a transition from *following* to *following*. Active/passive refers to movement by either the host (active) or other (passive) vehicle. Acceleration/deceleration refers to the type of transition that is due to the relative acceleration or deceleration between the host and other vehicles. Together, the states and transitions facilitate the determination of all possible driving situations involving two vehicles.

A few points should be noted from Table 3-1. There are a total number of 37 possible transitions. This includes the active and passive movements for the acquire, drop and switch transitions, and also includes transitioning from *cruising* to *cruising* which in this study means a lane movement of the host vehicle. Transitioning from a *closing, following* or *separating* state to its same state means a switch from one lead vehicle to another. The switch in this case could be due to movement by the host vehicle (active) or movement by the lead vehicle (passive). This latter case could in turn be a cut-in (lead vehicle moves into lane in front of host vehicle) or a cut-out (lead vehicle moves out of lane in front of lead vehicle), and could be determined by the relative range before and after the transition. Transitions between the *closing, following* or *separating* states may also occur due to accelerations or decelerations of the lead and/or host vehicles. A transition from *closing* to *separating* or from *separating* to *closing* involves either a switch of vehicles or a change in acceleration/deceleration. While the latter case would be unlikely (without an intermediate transition through the *following* state), it is possible (depending upon the acceleration/deceleration level and the sampling time) and is listed in the table for completeness. The 4 driving states and 37 possible transitions are further discussed and illustrated graphically in Appendix C.

3.4 Safety Surrogates and Measures of Performance

FOT participants logged about 184,000 kilometers, so it was recognized at the outset that the likelihood of even one crash occurring was low. In fact, no crashes related to use of the ICC system were observed during the field test. Therefore, if safety effects are to be inferred from the FOT data, it is necessary to examine surrogates for crashes – events or behaviors that may be reasonably related to an increased crash risk. The approach taken here is to examine a number of surrogate measures and evaluate whether trends are evident. Furthermore, surrogate measures are examined separately during normal driving and during safety-critical situations.

3.4.1 Basic Safety Performance Measures

A major intent of the safety evaluation was to search for plausible safety effects of the ICC systems. Thus, a comprehensive set of measures was felt to be necessary. Table 3-2 lists the basic safety measures of performance along with the safety implication for each, that is, the hypothesized relationship of the performance measure to safety and how they were organized and examined with respect to the *safety analysis framework*. The list includes commonly accepted surrogate measures of safety that are appropriate to the evaluation task at hand, namely, the evaluation of an ICC system in an operational environment.

Table 3-2 List of Basic Safety Performance Measures, Safety Implication, and Relationship to *Safety Analysis Framework*

Safety Surrogates and Performance Measures	*Safety Implication*	*Applicable States of Safety Analysis Framework*
Time-Headway	• Longer headways allow the driver more time to respond to impending situations and to control the vehicle. They are thus associated with safer driving behavior. • Traffic conditions may influence result.	Closing Following Separating
Velocity	• Higher velocities may increase the severity of collisions. • Higher velocities may increase closing rates and, thus, the probability and severity of collisions. • Variations in velo city may increase the probability of rear-end collisions.	All States
Acceleration	• Increased accelerations mean increased velocity fluctuations which may increase the probability of rear-end collisions.	All States
Braking Frequency	• Less braking indicates less control action required by the driver. • Fewer high braking events may be indication of a reduced probability of collision.	Closing Following Separating
Braking Force	• High negative acceleration is an indicator of increased probability of rear-end collisions • Variation in acceleration may increase the probability of rear-end collisions. • Higher braking force may indicate reduced headways and higher closing rates and, thus, a higher probability of collisions.	Closing Following Separating
Response Time	• Longer response times may be an indication of driver inattentiv eness and could increase the probability of collision • Longer response times may result in reduced headways and higher closing rates and, thus, increased probability of collisions	Closing Following Separating

In most instances the hypothesized relationship refers to the meaning of the direction of the safety impact, e.g., an increase in the time-headway measure means a positive safety effect. Although the directional relationships between the surrogate measures and safety are generally accepted (Perez 1996), the current literature is lacking on quantification of these relationships.

Since all the measures reflect a longitudinal driving component, they are considered appropriate to the evaluation of the ICC system, which is designed to maintain driver-set velocities and time-headways. **Braking frequency, braking force and acceleration** indicate specific actions taken by the driver to control the vehicle relative to developing roadway situations. **Driver response time** provides on indication of how long it took the driver to respond to particular situations. **Velocity, closing rate, and headway** are also key longitudinal performance measures that characterize the driving situation in ways that can be related to safety.

3.4.2 Safety-Critical Performance Measures

Safety-critical performance measures are used to assist in evaluating driving behavior during safety-critical situations defined in this study as occurring during closings and pre-crash scenarios. As mentioned in Section 2.6.1, closings are defined as driving situations where the closing rate is greater than 1.5 m/s and the time headway is less than 2.4 seconds. Pre-crash scenarios focus on the types of dynamics that most commonly precede rear-end collisions and stem from current NHTSA work to enhance collision databases. These scenario types are based on the pre-crash collision definitions associated with the NHTSA GES database. The rate of occurrence of pre-crash scenarios is postulated to be positively correlated to the rate of occurrence of collisions.

Table 3-3 lists additional safety-critical performance measures in this study. These measures are used in conjunction with those in Table 3-2 to examine driver behavior in the context of safety-critical situations.

Table 3-3 List of Safety-Critical Performance Measures, Safety Implication, and Relationship to *Safety Analysis Framework*

Safety Surrogates and Performance Measures	*Safety Implication*	*Applicable States of Safety Analysis Framework*
Close Calls	• Fewer situations of reduced headway and higher closing rates may reduce crash potential. • Some drivers may be using cruise control (both CCC and ICC) in a manor that results in very close headways and high closing rates.	Closing
State Space Boundary Crossings	• When below these boundaries there is less headway and higher closing rates, thus, an increased probability of collisions.	Closing
Closing Rates	• Lower closing rates may reduce the probability and severity of collisions.	Closing

In the absence of collisions, the **close calls** measure was postulated to be one of the more important measures of safety. Close calls are defined in section 3.9.1.7 relative to the video trigger. Compared to the other basic measures, which tend to be more *distal* to (or removed from) the ultimate safety outcome, i.e., collisions, the close call measure was felt to be more *proximal* (or connected) to the safety outcome. The close call measure is associated with the closing state context of the *safety analysis framework*.

The remaining two measures are new measures that were developed in this study to provide a better understanding of the safety effects.

The **state space boundary crossings** provide an integrated set of objective near miss measures. That is, they are measures expressed in terms of the state space variables, range and range rate, and a required deceleration level to achieve a minimum range. Each boundary integrates these variables into a single measure of driving hazard, namely, the boundary crossings.

The state space boundaries are defined as a set of curves in the range-versus-range-rate state space. The state space boundaries are placed in the upper left quadrant of the range-versus-range-rate space and are spread somewhat uniformly above the abscissa. The closer the curves are to the abscissa, the closer the driving situation, represented by a point on that curve, is to a collision situation. In other words, the curves closer to the abscissa are indicative of a relatively higher hazard potential.

State space boundary crossings allow focus of the safety analysis in critical state space zones, namely closing situations where the relative range between the two vehicles is near zero.

The state space boundaries are defined and described in Section 3.9.1.6. Also included in this section are the equations and parameters for each of the boundaries, as well as the interpretations and constraints with their use.

Closing rate is defined as the velocity difference between the lead and host vehicles and provides a direct performance measure associated with the closing state.

3.5 Safety Analysis Methods

3.5.1 Treatment of Data

Several conventions were followed in the analysis and reporting of the ICC evaluation. One of those conventions is that the driver is the primary unit of analysis. Thus any average or other characterization of travel with ICC is based on statistics where the driver is the sample unit. For instance, in reporting the percent of miles driven on freeways we first compute the percent for each driver, then average over drivers. This can yield different results than summing the miles driven on freeways (irrespective of driver), and then dividing by the total miles driven by all drivers. There are two major benefits to using the driver as the unit of analysis. One advantage is that this method gives equal weight to all drivers. This prevents a few high-mileage drivers from dominating the results. If the sample were large, and carefully selected to be representative of the entire driving population, then one might not need to perform a driver-based analysis. However, ICC participants were selected based on equal representation of age, gender, and previous cruise control usage from a selected area of residence. Therefore, even if the sample were larger, it would still not be representative of the general driving population.

3.5.2 Analysis Filters and Constraints

Unless mentioned otherwise in the body of the report, all analysis was subject to the following filters and constraints:

- Only velocities greater than 40 km/h were analyzed. Since the cruise control modes can only be operated at velocities above 40 km/h, this constraint focused the analysis where similar comparisons could be made.
- All snow trips were removed. Pilot tests revealed that the sensor malfunctioned when it snowed and when snow accumulated on the bumper.
- Driving outside the coverage zone was excluded. Roads were classifiable within a 11 county region using a GIS/GPS map matching algorithm (see below.) Road classification was considered essential for a proper understanding of safety

effects. The resulting analysis placed emphasis on two road types: freeways and arterials.

- Analysis involving a lead vehicle required that the lead vehicle be a valid target (determined by the Leica/UMTRI sensing system), that the target last longer than 0.5 seconds and that the range to the target change by no more than 20 meters in one deci-second.

In addition to these filters and constraints, a 5 minute total freeway exposure requirement (summed over trips) was imposed on the headway analysis (see Section 3.8.1) since a few drivers used the ICC system for only a few seconds at unusually long headways. The net effect, otherwise, would have been to include longer headways that were not considered to be appropriate.

Finally, the states and transitions analysis imposed a number of criteria to differentiate the types of states and transitions. These criteria are described completely in Appendix C *Driving State Identification Tool.* One of these criteria is the use of 2.4 seconds as a boundary on the far headway bin. This criterion became the basis for differentiating what is referred to as a cruising state (with or without a lead vehicle present beyond a 2.4 second headway) from the remaining states, *closing, following, or separating*, in which a lead vehicle was present within a 2.4 second headway.

3.5.3 Overview of Analysis Tools

In the conduct of the analysis, a number of tools were developed and applied. These are summarized next. Complete descriptions are given in the appendices.

GPS/GIS Map Matching Tool: The purpose of this tool was to automatically determine road type and introduce this variable into the database. Nine types of roads were classifiable. These nine types were consolidated into five for purposes of the analysis. The GIS database covered 11 counties in Southeast Michigan where most of the travel by the participants was expected to occur. This tool is described in Appendix F.

Driving State and Transition Identification Tools: The purpose of these tools was to determine specific driving states and transitions from the raw data that was obtained by the data acquisition system. The driving states were: *cruising, closing, following,* and *separating.* The transitions were: *acquire, drop, switch,* and *accelerate/decelerate.* In addition, a determination was made as to whether or not the transition was the result of a lane movement by the host vehicle (active) or not (passive). These tools are described in Appendices C and D.

Congestion Model: The purpose of this tool was to automatically determine the level of congestion and introduce this variable into the database. The Highway Capacity Manual (HCM) terminology for level of congestion was adopted for this study, namely *Levels of Service* A, B, C, D, E, and F. This model is described in Appendix G.

Video/Digital Data Integration Tool: The purpose of this tool was to associate the forward looking videos that were captured during the operational test with the digital data. This tool allowed the analyst to determine driver response times, close calls, and scenarios that were not determinable from the digital data. This tool is described in

Appendix H *Video/Digital Data Integration Tool* and Appendix I *Video Classification Training Manual.*

3.5.4 Statistical Issues

When comparing means, to determine whether there were significant differences between them, repeated-measures analysis of variance was typically used. The repeated-measures analysis of variance treats each subject (driver) as his, or her, own control. That is, in the ICC FOT each driver was evaluated on their unique use of manual, CCC and ICC. The repeated-measures analysis accounts for variability in dependent measures that is attributable to the subject (driver), and thus reduces the statistical error that would otherwise result. Typically, this results in a far more powerful statistical test than would be possible if the relationship between scores from the same drivers were ignored, or if the driver were treated as just another independent variable. However, there is a cost to the repeated-measures analysis. Repeated-measures analysis can reduce statistical power if there is no correlation between scores attributable to the driver variable. Of more importance to the ICC analysis, is the fact that a repeated-measures analysis requires that each driver have a score for each repeated measure. That is, an ICC driver can only be represented in a repeated-measures test if he has a score for the dependent measure for all three levels of cruise control: manual, CCC, and ICC. In some instances missing scores did result in considerable diminution of sample size. For instance, many drivers who used ICC on arterials did not use CCC on arterials. Repeated-measures analyses that included manual, CCC, and ICC as levels of the cruise mode variable excluded these drivers. Where warranted, we have addressed the reduction in sample size by doing pairwise comparisons between modes (e.g., ICC versus manual). In other cases we report the repeated-measures statistic based on all three modes, but show that inclusion of all the data would not have changed the conclusion, by displaying means and standard error statistics for all drivers, regardless of whether there are matching scores for the other modes.

The *F* statistics reported here are based on univariate repeated-measures analysis of variance. There are several assumptions implied by the usual interpretations of this statistic. The analysts have carefully examined whether the data appear to be consistent with those assumptions, and have taken precautions when other statistical tests have indicated the data do not meet those assumptions. These precautions include verification that differences reported would still be significant if: (a) appropriate adjustments were made to compensate for the failure to meet assumptions, and, or, (b) the same conclusion would be reached using the multivariate approach to repeated measures. To maintain consistency and simplicity, only the unadjusted univariate *F* statistics are reported. However, these statistics are only reported when they are consistent with appropriate alternative repeated-measures statistics, and, or, the assumptions of the univariate model have been met.

Besides the *F* statistic, other inferential statistics used in this report include the *t* statistic, and the C^2 (Chi-square) statistic. The *F* and *t* statistics are typically used to determine whether there are statistically reliable differences between sample means. The C^2 statistic is typically used to determine whether there are statistically reliable differences in frequencies. [1]

All inferential statistics are presented in the text in the following format:

Statistic Name (degrees of freedom) = Statistic Value, Probability < x.

Thus the *F* statistic appears as:

$F\ (df_{numerator},\ df_{denominator})$ = value, $p <$ value.

Except where specifically noted, only results with *p* values less than 0.05 are reported. Exact *p* values, which are commonly reported by computerized statistics packages, are not reported, but rather, where *p* values are less than 0.01, or 0.001, then the smallest of these values that was exceeded is reported. The *p* value is the only statistic of primary concern: it represents the probability that the reported finding resulted from chance variation in sampling, rather than from the influence of the independent variable(s). It is conventional in scientific studies to use 0.05 as an acceptable probability of making a type I error – accepting a finding as real when it is actually due to random sampling variability.

On graphs, error bars are used to represent two standard errors of the mean. The standard error of the mean is the expected standard deviation of means of a given sample size. In general, any mean that lies outside two standard errors is significantly different, at the 0.05 level, from the represented mean. Qualifiers on this generality include the assumptions that means compared using this technique come from similar sized samples with similar, normally distributed, variances.

3.6 Cruise Control Usage Results

3.6.1 Usage on All Roadways

The safety analysis begins with an examination of where and under what conditions ICC participants drove, and where and under what conditions they used the ICC system. Exposure is a critical factor in assessing safety. In the extreme case, if users have no exposure to a system, i.e., they don't use it, then the system has no safety effect. Furthermore, given that the system is used, generalizations concerning safety are only appropriate to conditions from which sufficient observations have been obtained. Thus it is important to know how much driving field test participants did on each road type; under what conditions they drove; and for what proportion of driving on those roads and under those conditions the participants elected to engage the ICC system.

The roads in this study were classified into the following types: *freeway, state highway, arterial, ramp, other, and unclassified.* Most of the roads that could not be classified were outside the eleven county area covered by the GIS database.

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[1] The reader is referred to statistics textbooks for further discussion of the uses and interpretation of these statistics. Recommended statistics references include Hayes (1973) for a academic discussion of all three statistics, Keppel (1973) for a clear and concise presentation of analysis of variance, or Tabachnick and Fidell (1996) for a step by step guide to the analysis process.

The *freeway* classification refers to limited access roadways including the US Interstate system. The *state highway* classification accounted for only four percent of total exposure. This classification was composed of mostly divided highways that may have some limited access sections, but also may have signalized sections. The *arterial* classification includes most non-limited access roadways that are not classified as local roads or feeders — thus the arterial classification includes both urban arteries and rural highways. The *other* classification includes local roads, feeders, and unimproved roads.

Although the GIS database that was used to classify roadways included two ramp classifications (high velocity and low velocity), the majority of *ramps* were identified by an alternative classification rule. That rule was: if there is a transition from freeway to arterial, freeway to ramp, or arterial to freeway, then the preceding 400 meters are classified as ramp. Without this rule, the roadway classification program had a tendency to miss ramps entirely, or miss most of the extent of ramps, as it was biased towards choosing the higher-class roadway when GPS coordinates were in the proximity of more than one road. Ramps, by their nature, are nearly always in proximity to higher-class roadways. With the exception of some video analysis, this report does not include analysis of data identified with ramps. In part, analysis of ramp data was avoided because of the imprecise manner in which ramps were classified. However, other considerations also went into the decision to exclude ramp data from analysis. Some of these were:

- participants had been instructed to avoid use of ICC on ramps,
- the geometry of ramps was such that guard rails and other objects were often interpreted as preceding vehicles by the ICC system,
- ramp driving frequently includes rapid acceleration or deceleration unrelated to the use of cruise control, and
- there is very little ramp data to support analysis: only three percent driving time was on ramps, and ICC was engaged for only four percent of that fraction.

The 400-meter criterion was intended to favor a ramp classification. That is, it was deemed more important to exclude data possibly from ramps than to capture the first or last few meters of freeway or arterial travel. Although the study of driving behavior in merge areas is important, and safety issues regarding cruise control use in merge areas deserve attention, the quality of the GPS roadway classification algorithm does not make the ICC FOT data a good choice for study of these issues. Testing and validation of the GIS road classification algorithm are documented in Appendix F.

Figure 3-2 shows average roadway exposure, defined in terms of time and distance, across the 108 drivers. The average participant drove 1,776 km and accumulated 29 hours of driving time. Because the ICC system did not function below 40.3 km/h (25 m/h), exposure is shown in Figure 3-3 only for travel above 40.3 km/h. The average participant drove the ICC vehicle for 19 hours and a distance of 1,646 km at velocities above 40.3 km/h. Travel on unclassified roads was primarily outside the area for which map data were available (see Chapter 2). The mean percentages of time and distance traveled are shown for classified roadways in Figure 3.4. It can be seen that for the average driver, because of the higher travel velocities, freeways accounted for 43 percent of travel time, but 54 percent of travel distance. It can also be seen that arterials accounted for 38 percent of travel time, and 31 percent of travel distance. These two road types thus dominate in both travel time and distance when velocities are greater than 40.3 km/h.

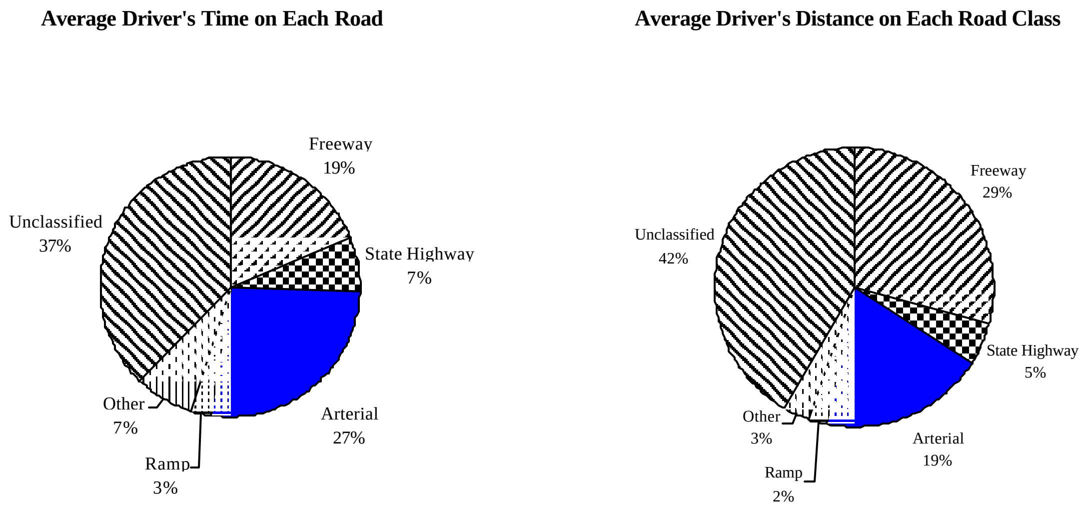

Figure 3-2 Average Driver's Road Class Exposure (N = 108) Based on Travel Time (Left) and Distance (Right).

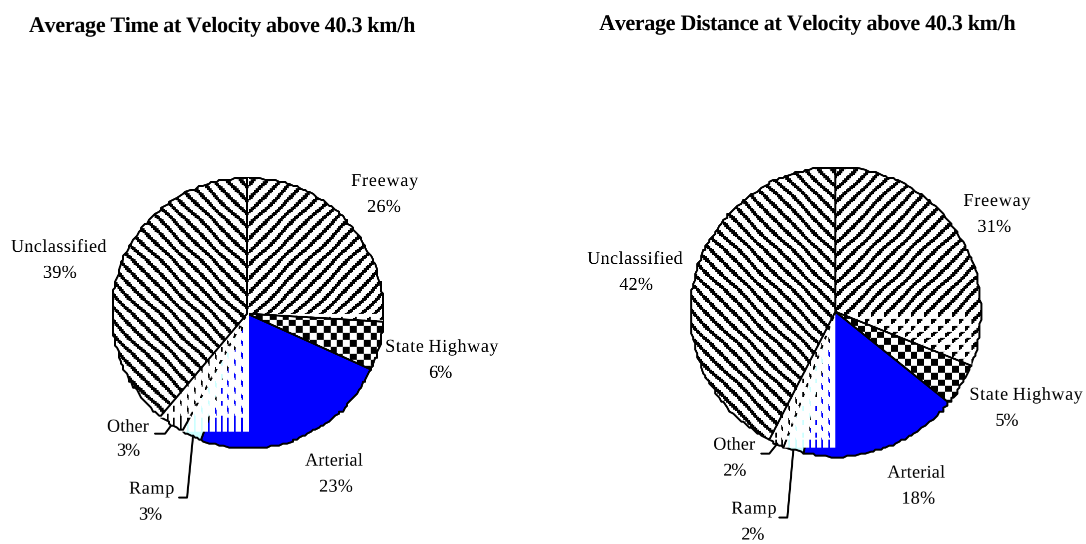

Figure 3-3 Road Class Exposure at Velocities above 40.3 km/h (25 m/h).

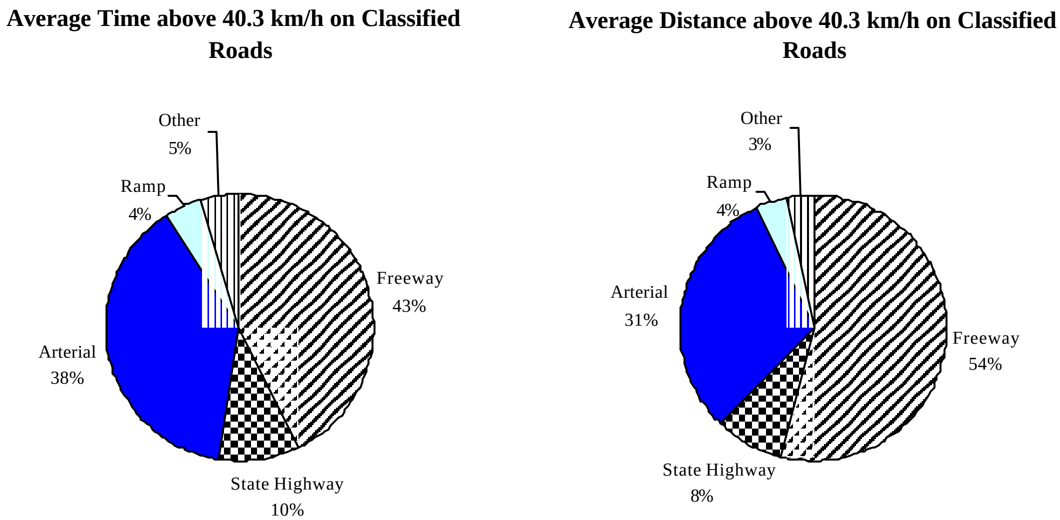

Figure 3-4 Average Driver's Road Class Exposure on Classified Roads within the Eleven-County Southeastern Michigan Area

The above averages do not reflect differences in exposure among drivers. To provide an indication of the variability in exposure among drivers, Figure 3-5 shows the number of drivers with less than one hour of driving on each road class, as well as the number with more than one hour of driving on each class. It can be seen that most of the drivers had an hour or more of exposure on freeways. A substantial number had an hour or more of exposure on arterials. It is important to note that two drivers were missing GPS coordinates from their data logs. For these two drivers, all driving was associated with unclassified roadways.

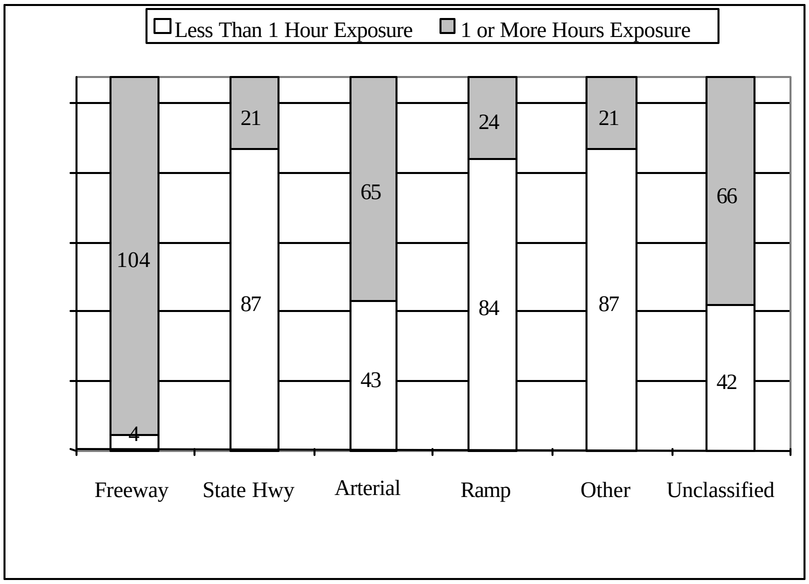

Figure 3-5 Distribution of Drivers with More or Less than 1 Hour Exposure to Each Road Classification

The percent of distance in manual and conventional cruise control mode are shown for the first week of the test, when CCC was available, in Figure 3-6. The percent of distance in each mode is shown separately for each road classification, and the average total distance per driver is shown in the lower right corner of each pie chart. It can be seen that the majority of travel during the first (baseline) week was on freeways, arterials, and unclassified roads. CCC was used for more than 50 percent of the distance traveled on unclassified roadways. Because the unclassified roads were largely outside of the Detroit metropolitan area, it might be assumed that most of this usage was outside of congested urban areas.

The percent of distance traveled in manual and ICC modes is shown for the latter weeks of the test, when ICC was available, in Figure 3-7. When contrasting usage of ICC with CCC, the most striking change is in freeway usage: whereas CCC was used for only 41 percent of freeway driving within the Detroit metropolitan area, ICC was used for 62 percent of travel distance, representing a 50 percent increase in cruise usage. Percentage changes on the other road classifications were minimal, particularly when total travel distance is considered.

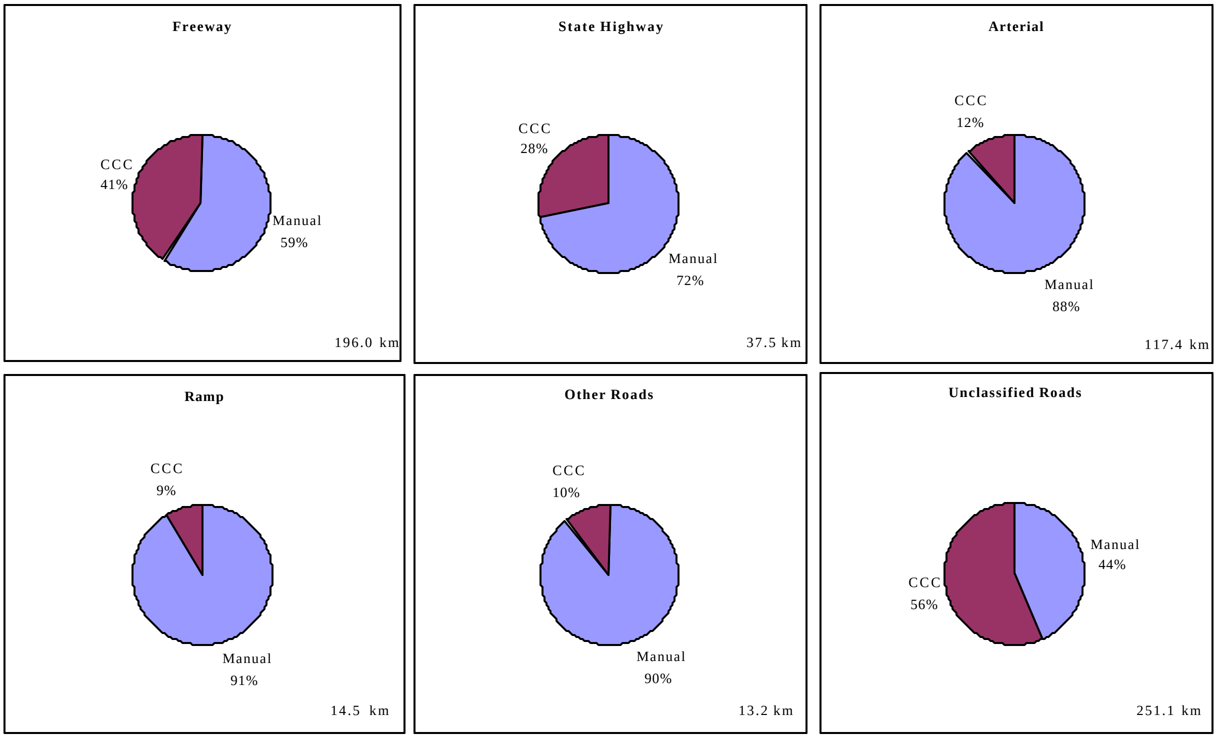

Figure 3-6 Average Distance Driven on Each Road Class in CCC and Manual Modes When CCC was Available

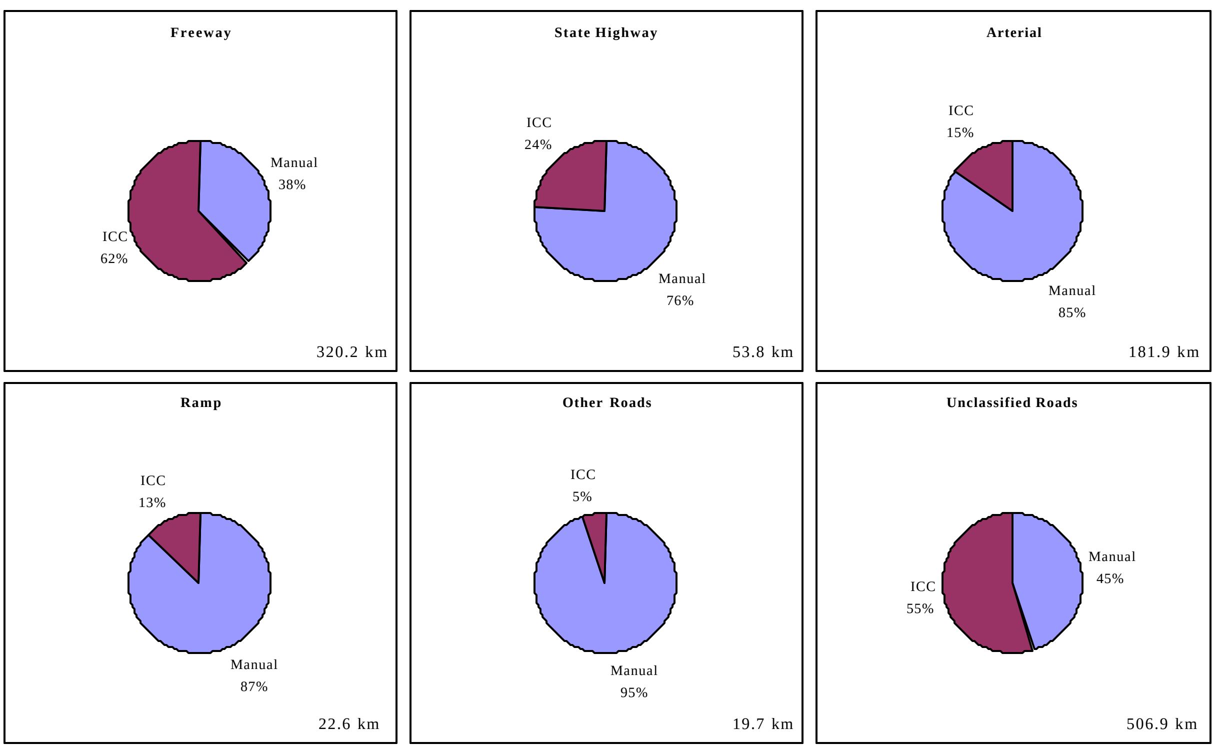

Figure 3-7 Average Distance Driven on Each Road Class in ICC and Manual Modes When ICC was Available

Figures 3-8 and 3-9 show the analogous percent of time on each road class during the weeks when CCC and ICC, respectively, were available. Contrasting usage as a function of time and distance shows that, as the expected average velocities increase, the percent of distance increases relative to the percent of time. Thus on arterials where cruise control can be expected to be used only where speed is relatively unimpeded, the percent of distance traveled in cruise control is large relative to the amount of time that cruise control is used.

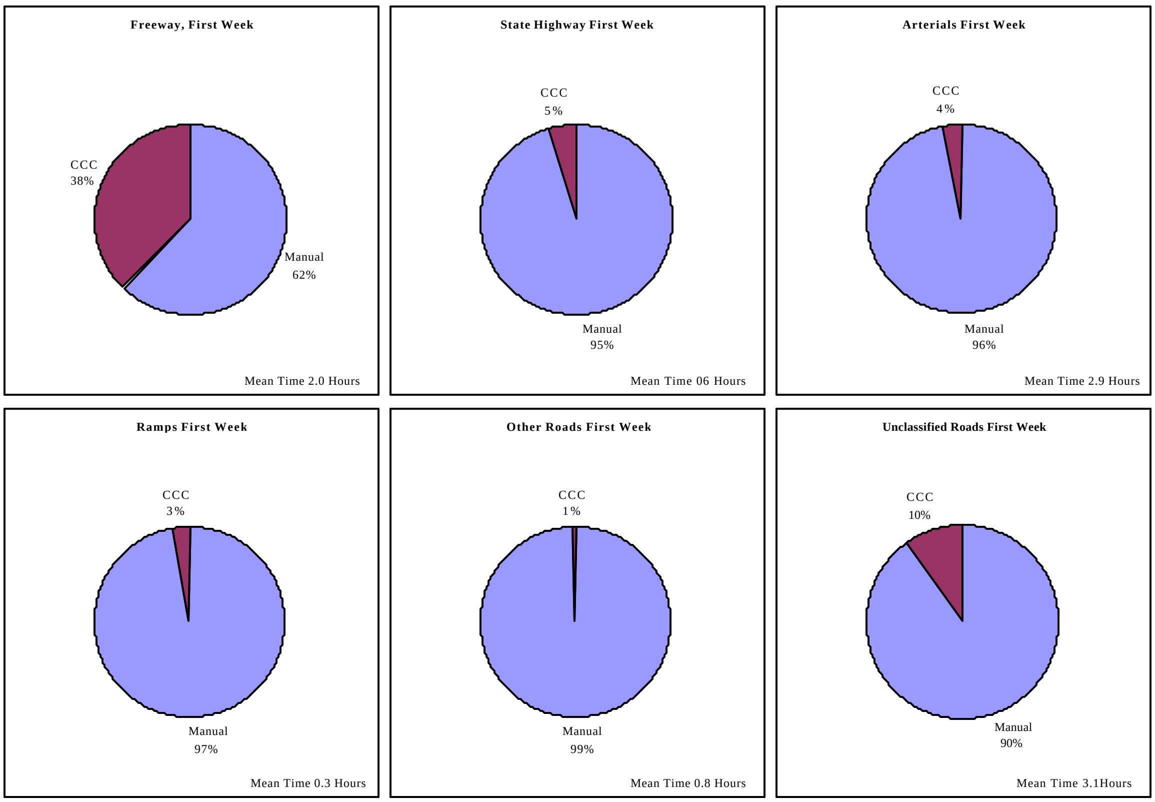

Figure 3-8 Average Time on Each Road Class in CCC and Manual Modes When CCC was Available

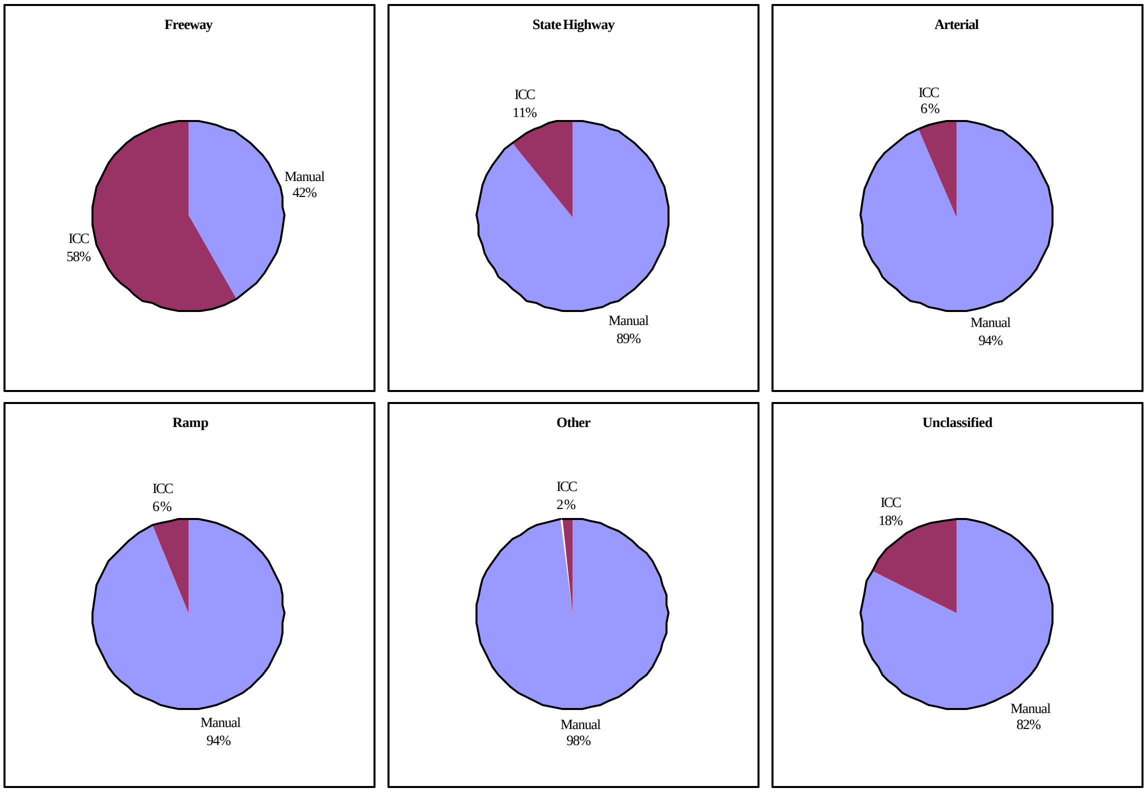

Figure 3-9 Average Time on Each Road Class in ICC and Manual Modes When ICC was Available

3.6.2 Usage on Freeways

Of the 108 drivers in the test, road class information was available for 106. The two drivers for whom GIS information was not available were females and members of the two-week participation group. One was middle-aged and claimed to be a prior nonuser of cruise control. The other was a young cruise control user. Of the 106 drivers with road class information, four did not drive on freeways during the first week, the week CCC was available. Thus, comparisons of CCC usage versus ICC usage are based on 102 drivers who used the freeways during both periods of the test (CCC available and ICC available). Of the four drivers who did not drive on freeways during the first week, three were female, two were previous cruise control users, and all were in the 20 to 30 age group. The male was from the five-week participation group, the females were two-week participants.

3.6.2.1 Usage as a Function of Prior Cruise Control Experience, Age, Weeks of Participation, and Weeks into Test. On freeways, ICC received considerably more use than conventional cruise control, F (1, 96) = 88.1, $p < 0.001$. Participants who said they were cruise control users prior to participating in the test were more likely to use either a cruise control system than participants who said they had not previously used cruise control. Furthermore, the difference between ICC use and CCC use was less for users than for non-users, F (1, 96) = 5.5, $p < 0.05$. As can be seen in Figure 3-10, both prior users and nonusers used ICC more than CCC, but the difference between these groups was smaller with ICC. This suggests that if ICC systems were deployed more people would use them than use CCC, and current CCC users would use ICC more than they currently use CCC.

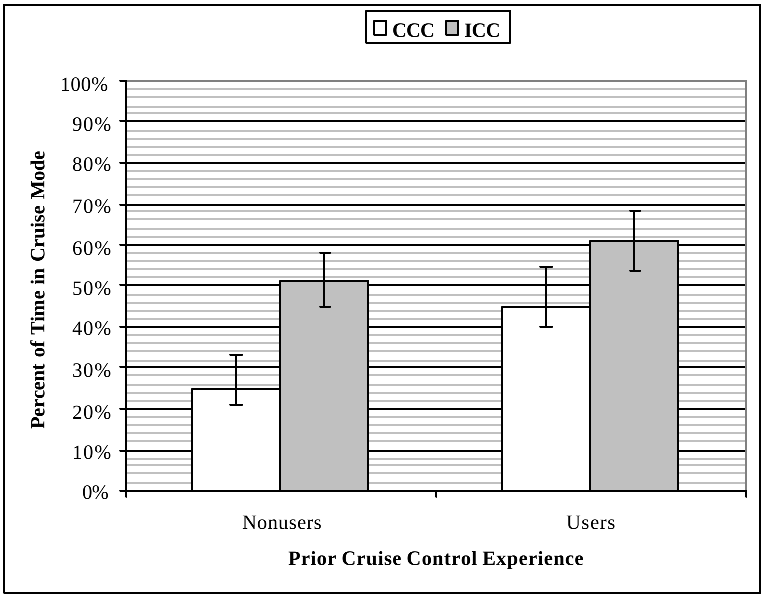

Figure 3-10 Percent of Time ICC and CCC Were Used on Freeways as a Function of Prior Cruise Control Experience

As can be seen in Figure 3-11, there was a trend for cruise control usage to increase with driver age, $F(2, 96) = 8.4$, $p < 0.001$. There was no significant difference in this trend as a function of prior cruise control experience or weeks of participation in the FOT.

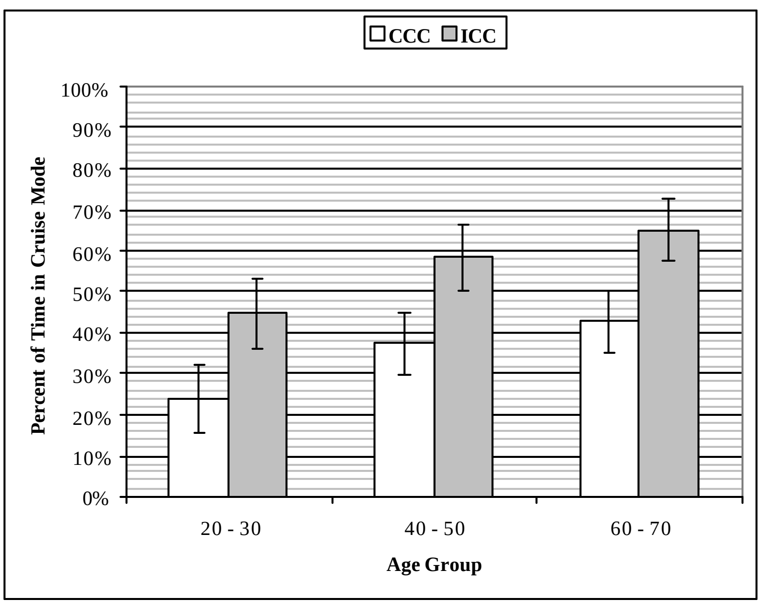

Figure 3-11 Cruise Control Usage on Freeways as a Function of Age Group and Cruise Control Mode

In Figure 3-12, it can be seen that ICC participants who had the vehicles for five weeks, four of those weeks with ICC available, used cruise control more than did participants who had the vehicles for two weeks. This finding is consistent with the finding that prior cruise control users use cruise control more, as all the five-week participants were prior cruise control users, whereas only half of the two-week participants were prior users. Interestingly, ICC usage was almost equal among two- and five-week participants. The difference in cruise usage as a function of length of participation was due to differences in usage of CCC during the first week. This finding was reflected in a week by cruise mode interaction, F (1, 96) = 7.5, $p < 0.01$. That is, use of both cruise modes combined was significantly more for the five-week group of FOT participants (who were entirely prior cruise control users.) To be included in this analysis, drivers had to have driven on freeways both the first week, when CCC was available, and the second or subsequent weeks when ICC was available. Actual use of cruise control was not required. There were 23 (out of 24) five-week participants included in the analysis, and 79 (out of 84) two-week participants.

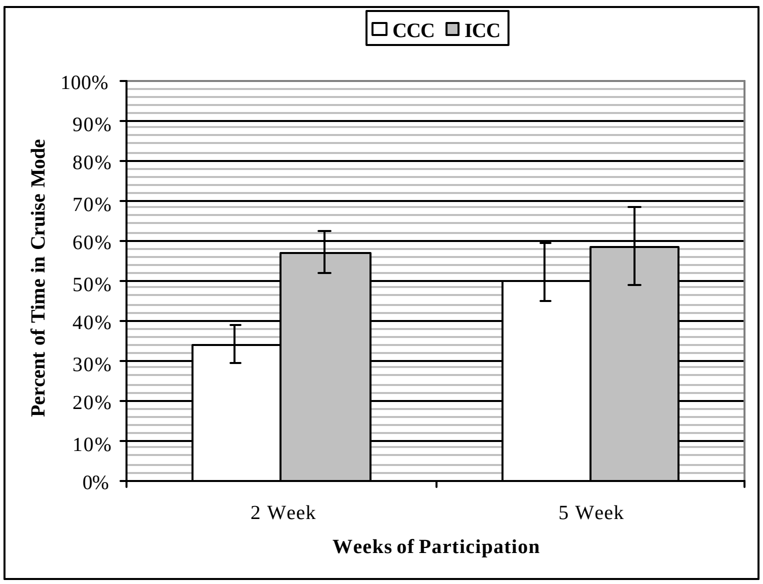

Figure 3-12 Percent of Cruise Control Use on Freeways as a Function of Weeks of Participation and Cruise Control Mode

For those users who had the ICC system available for four weeks, usage on freeways remained relatively consistent over the entire usage period. Figure 3-13 shows ICC usage on freeways plotted as a function of week into test for 19 five-week participants who drove on freeways each week. There was no statistically reliable trend in the percentage of time that ICC was engaged. That usage did not decline over the extended period suggests that the observed usage may be representative of long term usage, and not a product of demands of the test. As ICC usage by five-week participants did not differ significantly from that of two-week participants, it might be reasonable to assume that the behavior of the five-week participants was also representative of two-week users. One caveat on this assumption is that there were no nonusers among the five-week participants.

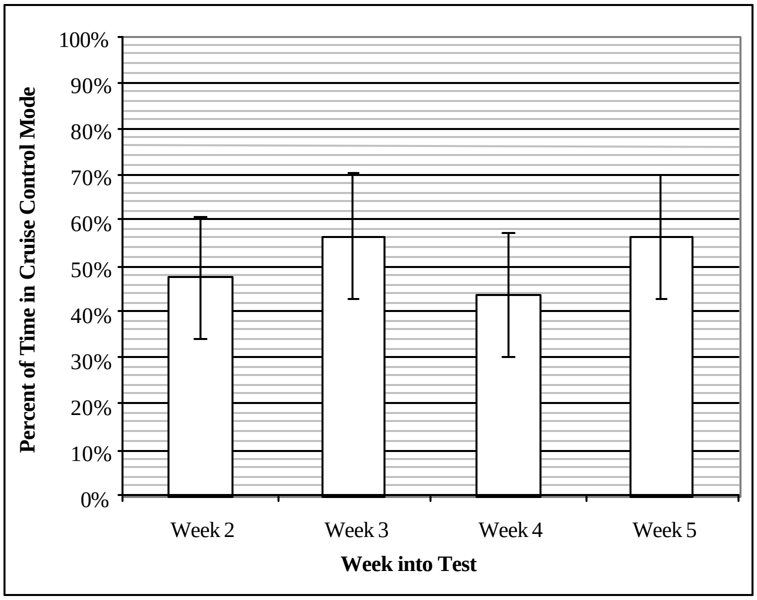

Figure 3-13 Percent of Time ICC was Engaged on Freeways as a Function of Week into Test (N =19)

Figure 3-14 shows that the average percentage of time drivers had cruise control engaged increased with trip length. With ICC, usage approached 60 percent of the time when trips were fifteen minutes or longer in contrast to about 38 percent usage for CCC. This suggests that for longer freeway trips, ICC usage would be about 50 percent greater than current CCC usage.

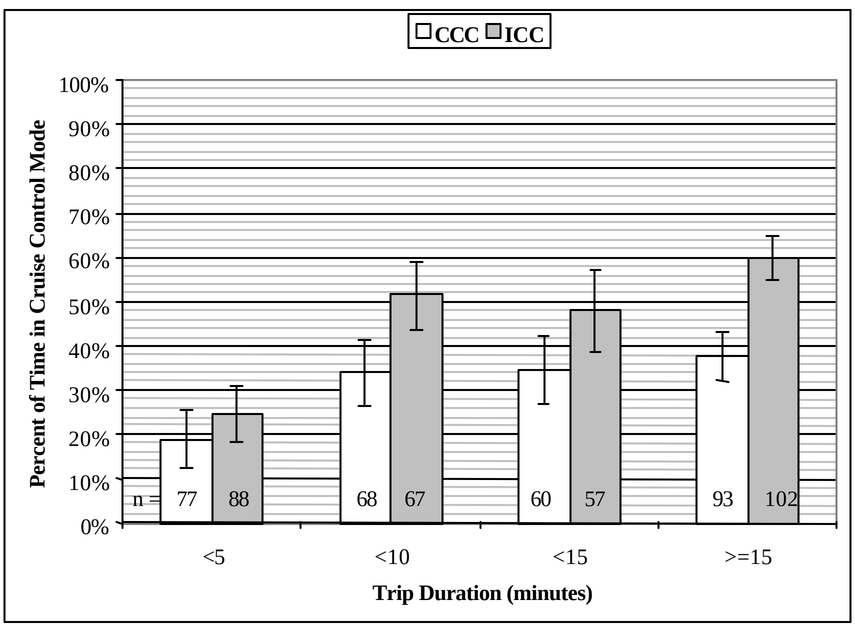

Figure 3-14 Cruise Control Use on Freeways as a Function of Trip Duration and Cruise Control Mode

In summary, on freeways ICC is used about half again as much as CCC. Like CCC, ICC usage increases with driver age. Individuals who say that they use conventional cruise control, tend to use ICC more than those who say they do not. However, both users and nonusers regularly used ICC more than half of the time that they traveled on freeways on trips greater than five minutes. Furthermore, nonusers had a significantly higher rate of ICC use than CCC use.

3.6.2.2 Usage as a Function of Congestion on Freeways. Figure 3-15 shows the percent of time the ICC vehicles were estimated to be in various levels of congestion when traveling on freeways at velocities above 40.3 km/h (25 m/h). The evaluation's level of service model was used to estimate congestion (see Appendix G). The model estimates that 40.3 percent of manual driving occurred in uncongested conditions (levels of service A and B) whereas 46.6 percent occurred in lower levels of service. The model was unable to classify the level of service for 13.1 percent of the manual freeway driving time. As can be seen in Figure 3-15, 68.8 percent of CCC driving was estimated to have taken place under levels of service A and B, and 59.2 percent of ICC driving was attributed to those levels of service. There was a 26.5 percent increase in exposure to levels of service C and D with ICC, relative to CCC. This is consistent with the suggestion that drivers used ICC more because the ICC system was able to control headways under these more demanding conditions.

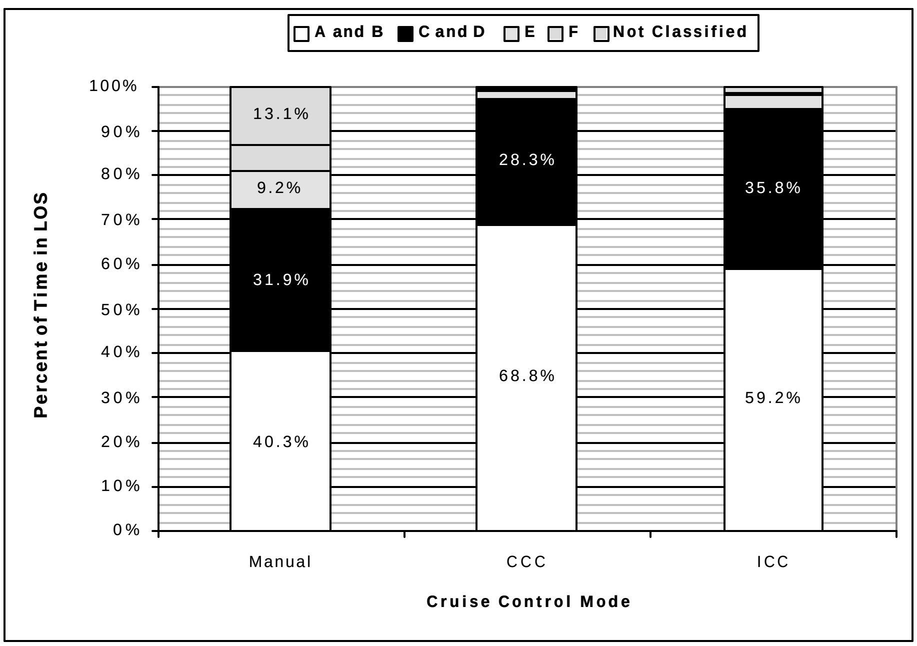

Figure 3-15 Percentage of Time on Freeways as a Function of Level of Service and Cruise Control Mode

Figure 3-16 expresses the same results as a function of the level of service for all drivers. The top figure shows the relative usage during week one when CCC was available, while the bottom figure shows the relative usage during the remaining weeks when ICC was available. The results indicate that, although there was a diminishing usage of either cruise mode with increased congestion, ICC was used more frequently than CCC at all levels of service, and the effect was more pronounced at higher levels of congestion. For example, ICC was used 5.6 times more than CCC at level of service E, compared to 1.9

times more than CCC at level of service C and D. Figure 3-17 expresses the results for the two-week drivers only and indicates that there was no change in these conclusions.

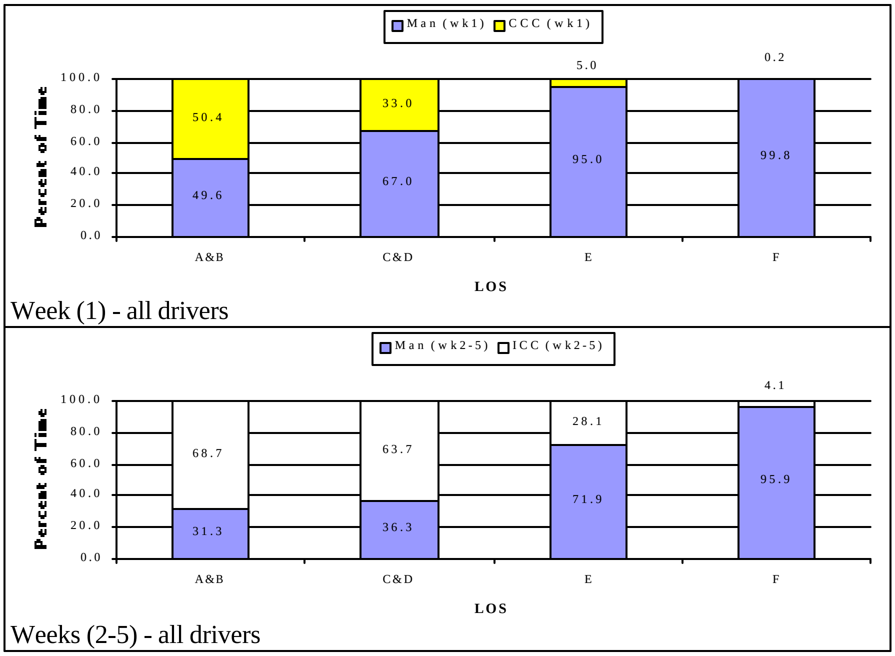

Figure 3-16 Percentage of Time on Freeways by Week as a Function of Level of Service and Cruise Control Mode for All Drivers

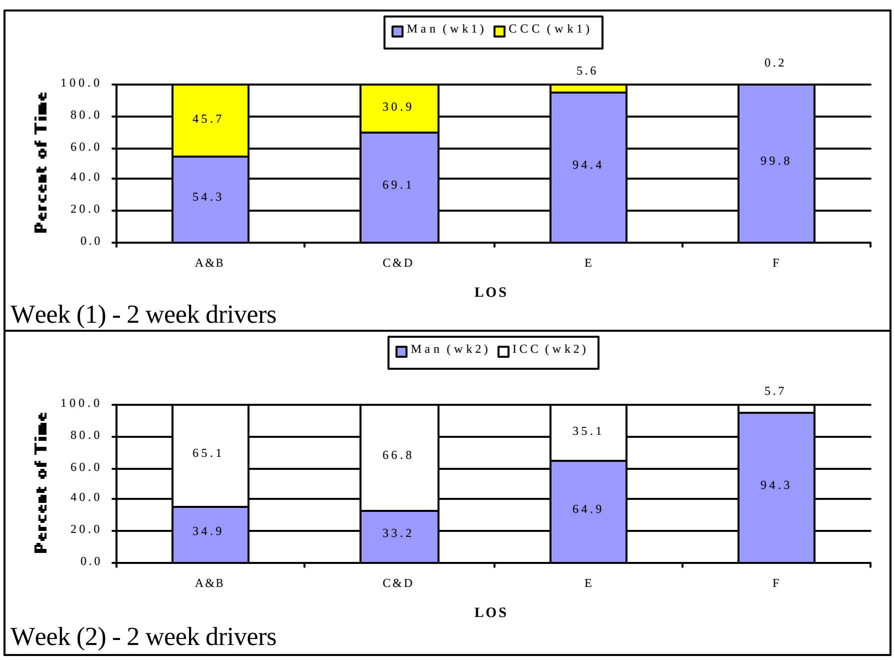

Figure 3-17 Percentage of Time on Freeways by Week as a Function of Level of Service and Cruise Control Mode for 2 Week Drivers

Figure 3-18 shows the velocity distributions by cruise mode and for each level of service. Clearly travel velocities are reduced for all cruise modes as the level of congestion increases (level of service decreases). Velocity can thus be an appropriate surrogate measure of congestion and is interpreted as such in the remainder of this report. The figure also indicates that the range of velocities for any given level of service is greatest for manual, and next for ICC, while CCC has the narrowest velocity range. The CCC travel velocities tend to be higher which is consistent with ICC and manual being used more during higher levels of congestion.

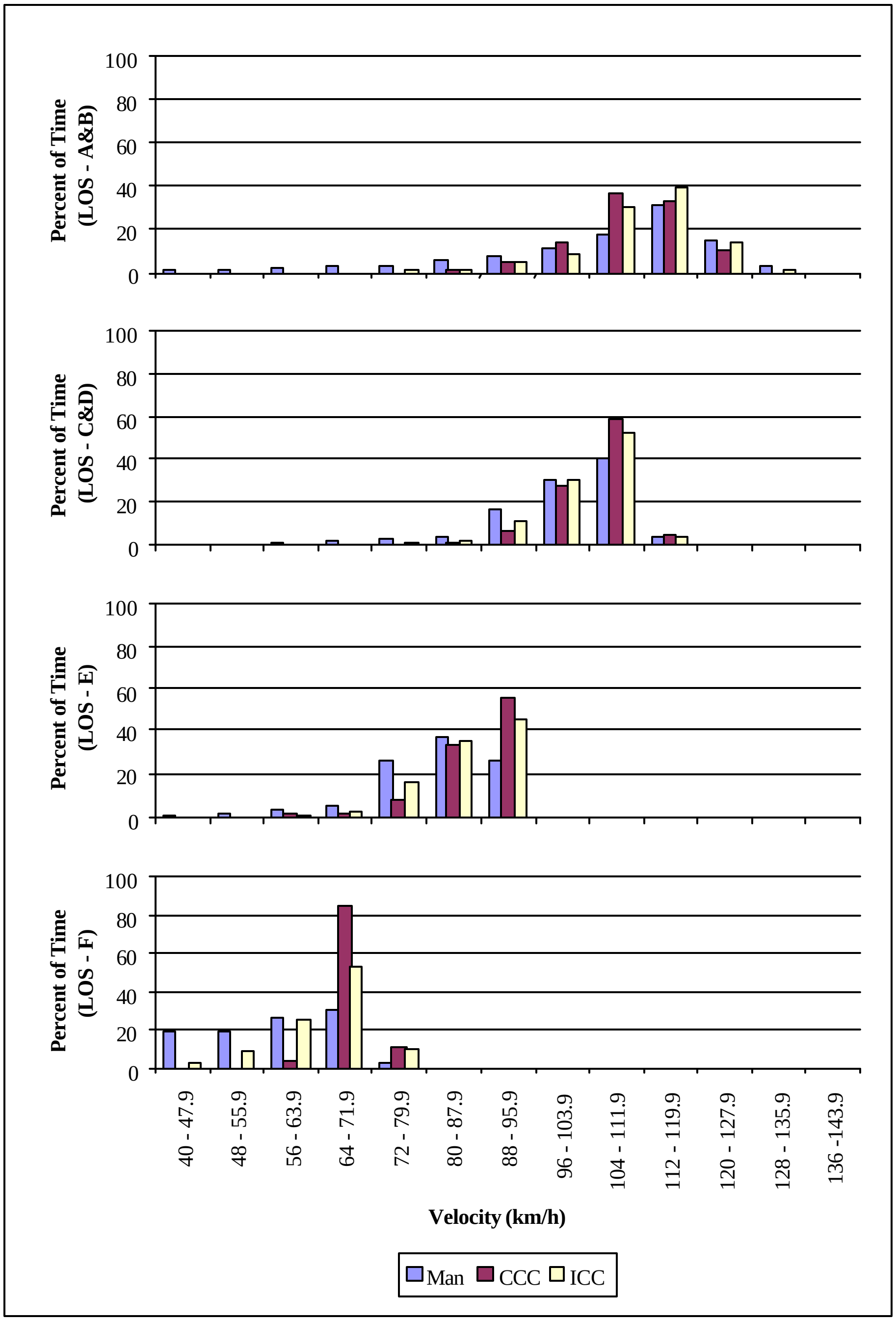

Figure 3-18 Velocity Distribution on Freeway as a Function of Level of Service and Cruise Control Mode

3.6.2.3 Usage as a Function of Velocity Setting and User Group on Freeways. The set velocity drivers chose when using cruise control was examined by comparing average set velocity with ICC to average set velocity with CCC. Mean set velocity was computed as the unweighted mean set velocity for that portion of trips that was on freeways. Previous cruise control experience and age group were included in this analysis as between group variables. The mean selected set velocity with ICC, 108.5 km/h, was significantly higher than mean set velocity with CCC, 106.6 km/h, F (1, 87) = 15.6, p < 0.001. Selected ICC set velocity declined linearly with age, F (2, 87) = 9.4, p < 0.001, and those who claimed to be previous CCC users chose higher ICC set velocities, F (1, 87) = 4.9, p < 0.05. The set velocity findings are depicted in Figure 3-19. There were no significant within or between group interactions.

Mean set velocities associated with the 1.0 s, 1.4 s, and 2.0 s headways settings were 110.7 km/h, 108.3 km/h, and 107.2 km/h respectively. The age group difference in headway preference is the most likely explanation for the variation of set velocity with headway preference.

ICC was associated with higher set velocity relative to CCC. However, this difference was small, probably too small to have a safety impact. Furthermore, as average velocities with ICC were lower than average velocities with CCC, set velocity was not the determining factor in average travel velocity. Therefore, even though ICC set velocities are slightly higher that CCC, it does not result in a negative safety effect.

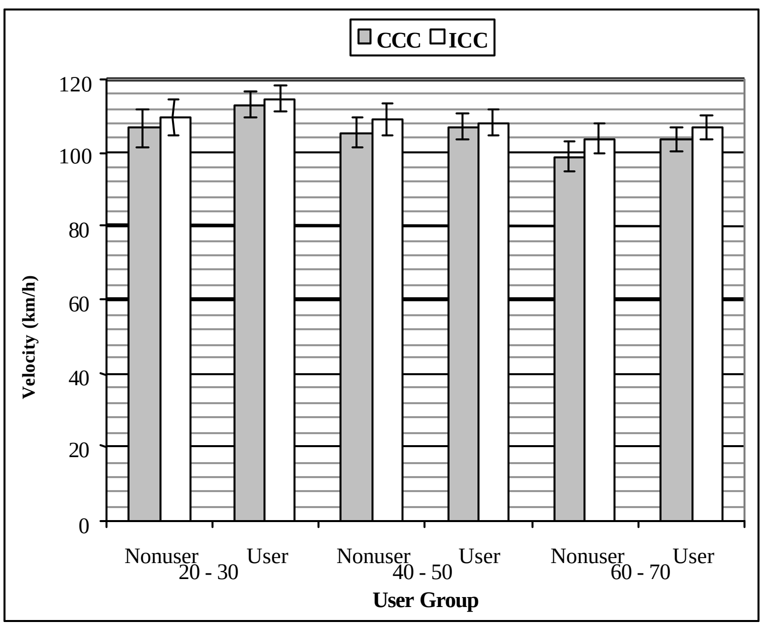

Figure 3-19 Cruise Control Set Velocity as a Function of Cruise Control Mode, Age Group, and Prior Cruise Control Experience

3.6.3 Usage on Arterials

There were 103 participants who drove on roads classified as arterials during both the first week of participation, when CCC was available, and during the latter weeks, when ICC was available. Of the three participants who did not have exposure to arterials both before and after ICC availability, all claimed to be prior users of cruise control. One was an older female, one was a young female, and one was a young male. The young male was a five-week participant.

3.6.3.1 Usage as a Function of Prior Cruise Control Experience and Age Group. Figure 3-20 shows cruise control usage on arterials as a function of cruise control mode and age group. As can be seen, cruise control use on arterials was minimal. However, overall ICC was used significantly more than CCC, $F(1, 97) = 19.3$, $p < 0.001$. Cruise control use (both CCC and ICC) increased with age, $F(2, 97) = 3.7$, $p < 0.05$. Prior cruise control use did not have a significant influence on use of either ICC or CCC use on arterials. Figure 3-21 is similar to Figure 3-20 but does not include time below the minimum speed at which CCC and ICC could operate, i.e., 40.3 km/h.

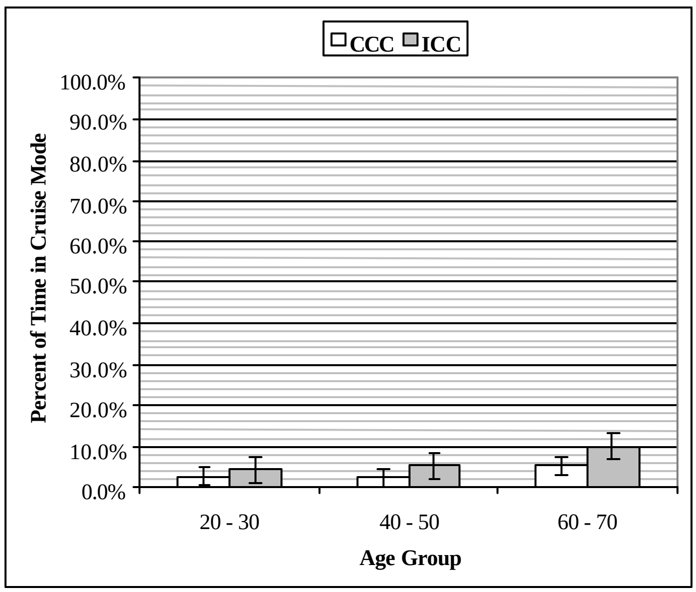

Figure 3-20 Cruise Control Usage on Arterials as a Function of Cruise Control Mode and Age Group

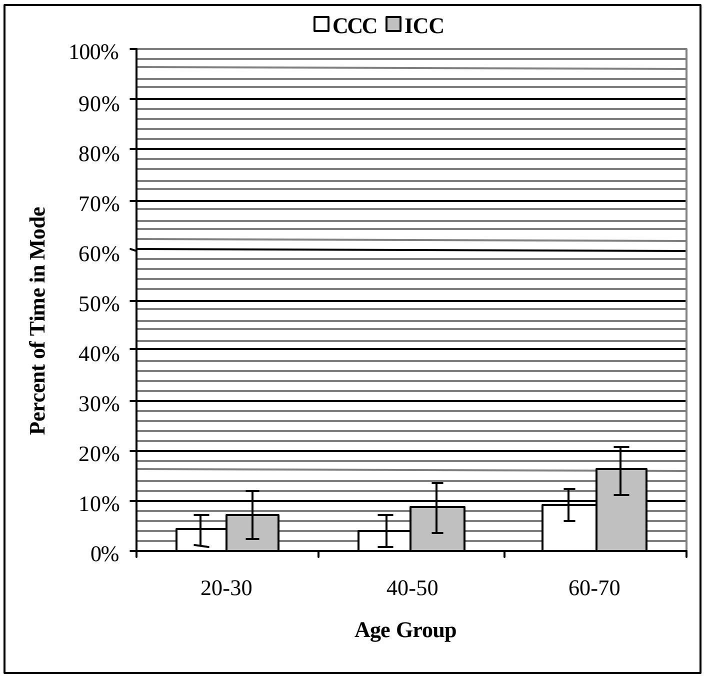

Figure 3-21 Cruise Control Usage at Velocities Greater than 40.3 km/h on Arterials as a Function of Cruise Control Mode and Age Group

Overall, ICC and CCC saw very little use on arterials. The average participant used ICC on arterials for only 10.5 minutes. Twenty-one drivers never used ICC on arterials.

3.6.3.2 Usage as a Function of Congestion on Arterials. Figure 3-22 shows the percent of time the ICC vehicles were estimated to be in various levels of congestion when traveling on arterials at velocities above 40.3 km/h (25 m/h). It is clear from the figure that drivers used cruise control on arterials, either ICC or CCC, mostly when traffic was light.

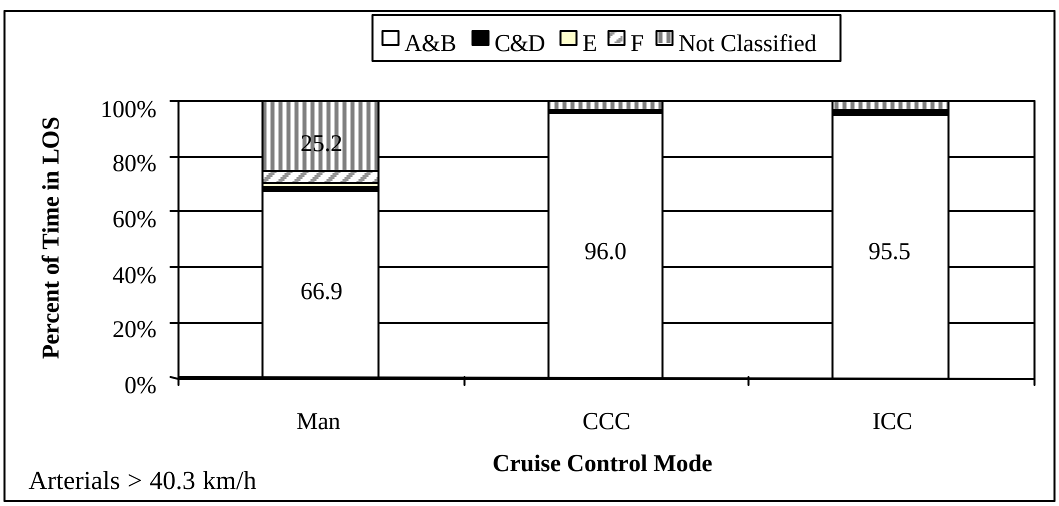

Figure 3-22 Percentage of Time on Arterials as a Function of Level of Service and Cruise Control Mode

Figure 3-23 expresses the same results as a function of the level of service for all drivers. The dominant effect is once again the very little usage of cruise control beyond Level of Service A and B. What little results there are relative to Level of Service, tend to parallel that for freeways. Namely, although there was a diminishing usage of both cruise modes with increased congestion, ICC was used more frequently than CCC at all levels of service, and the effect was more pronounced at higher levels of congestion. The levels of cruise usage on arterials was substantially less than the levels of cruise usage on freeways for all levels of service.

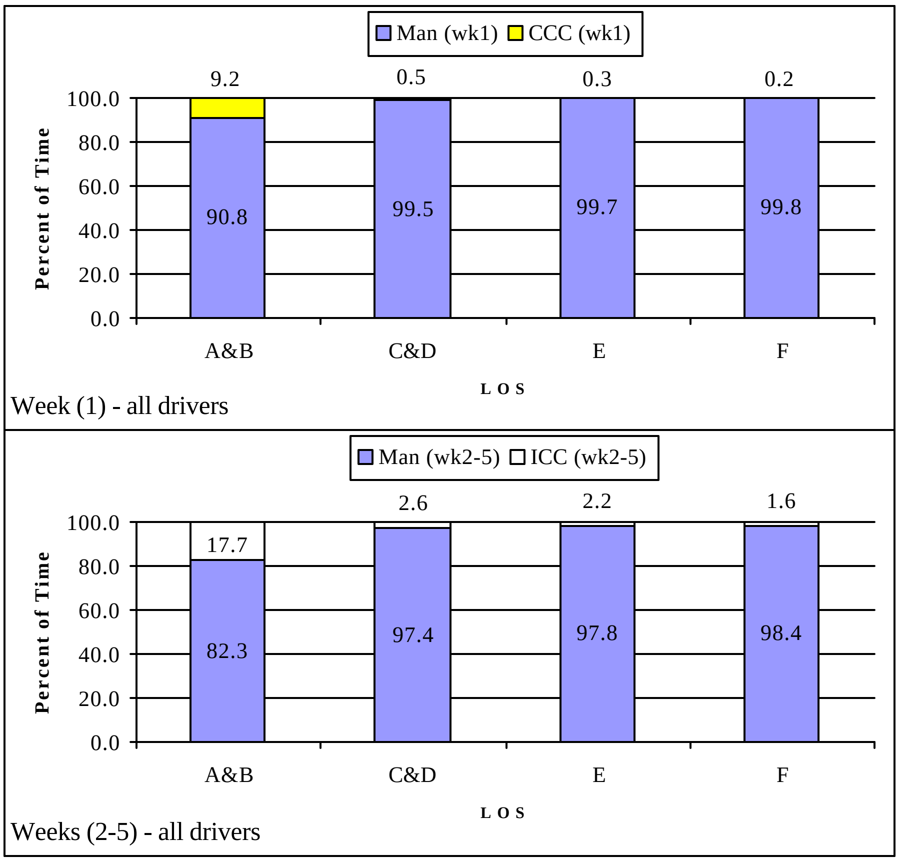

Figure 3-23 Percentage of Time on Arterials by Week as a Function of Level of Service and Cruise Control Mode for All Drivers

Figure 3-24 expresses the results for the two-week drivers only and indicates that, similarly for freeways, there was no change in the conclusions compared to the results for all drivers.

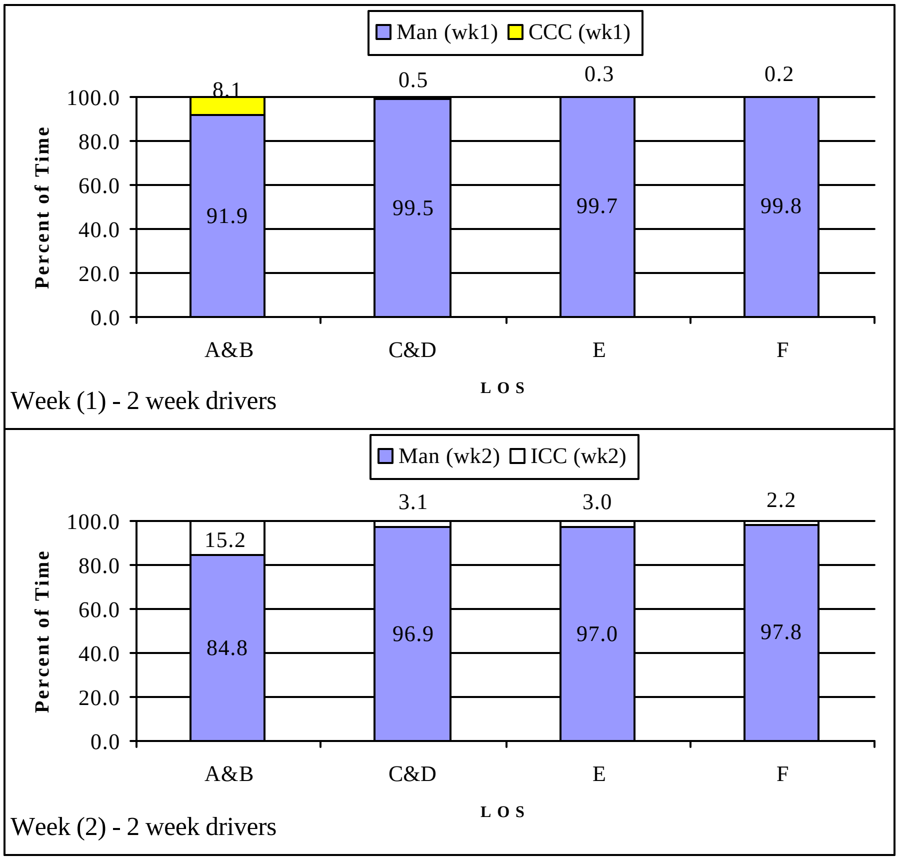

Figure 3-24 Percentage of Time on Arterials by Week as a Function of Level of Service and Cruise Control Mode for Two Week Drivers

Figure 3-25 shows the velocity distributions by cruise mode, and for each level of service. The travel velocities are substantially reduced and are all below 56 km/h for Level of Service C-F for all modes, compared to level of Service A and B. So, for whatever little driving there was during congestion, it was all done at the lower velocities. Any analysis on arterials in this study will therefore be restricted to Level of Service A and B, or interpreted as such. Level of Service A and B encompasses a wide range of velocities with the greatest range for manual. ICC shows a similar range to that for CCC.

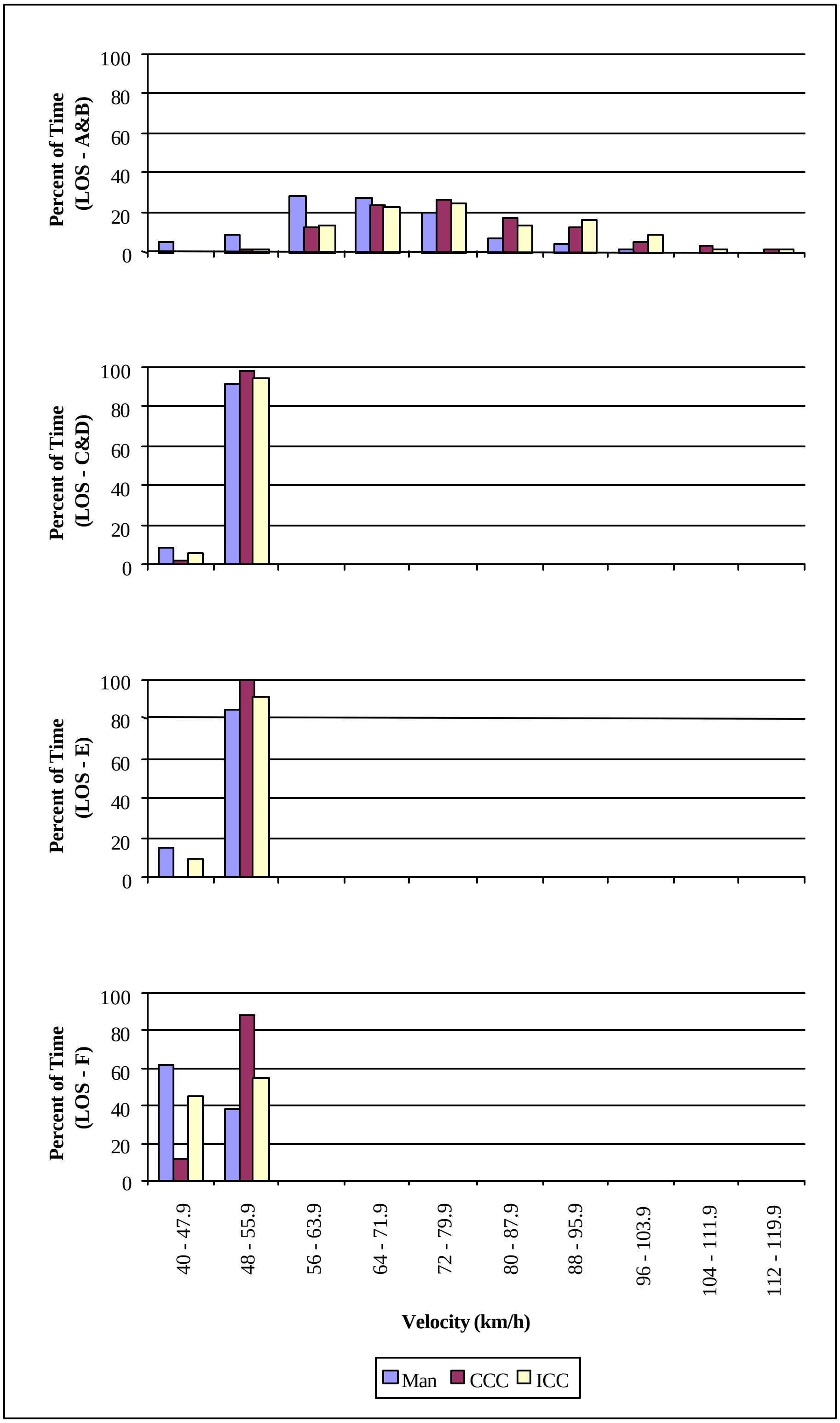

Figure 3-25 Velocity Distribution on Arterials as a Function of Level of Service and Cruise Control Mode

3.6.4 Usage as a Function of Velocity Setting – Freeways Versus Arterials

Figure 3-26 shows the distribution of velocity settings for the different ICC headway settings on freeways. Figure 3-27 shows the distribution on arterials. It is interesting that, consistent with the road types, drivers use higher velocity settings on freeways. On freeways the low end was about 80 km/h, while on arterials the low end was about 56 km/h. The 1.0 second headway setting was associated with higher velocity settings (greater than 112 km/h) on freeways. On arterials, the 1.0 second headway setting was used over a wider range of velocity settings including greater than 112 km/h and less than 64 km/h. It appears that the younger, aggressive drivers, who used the 1.0 headway setting most often, were the drivers that used higher set velocities, and perhaps attempted to drive during periods of congestion or near congestion on arterials.

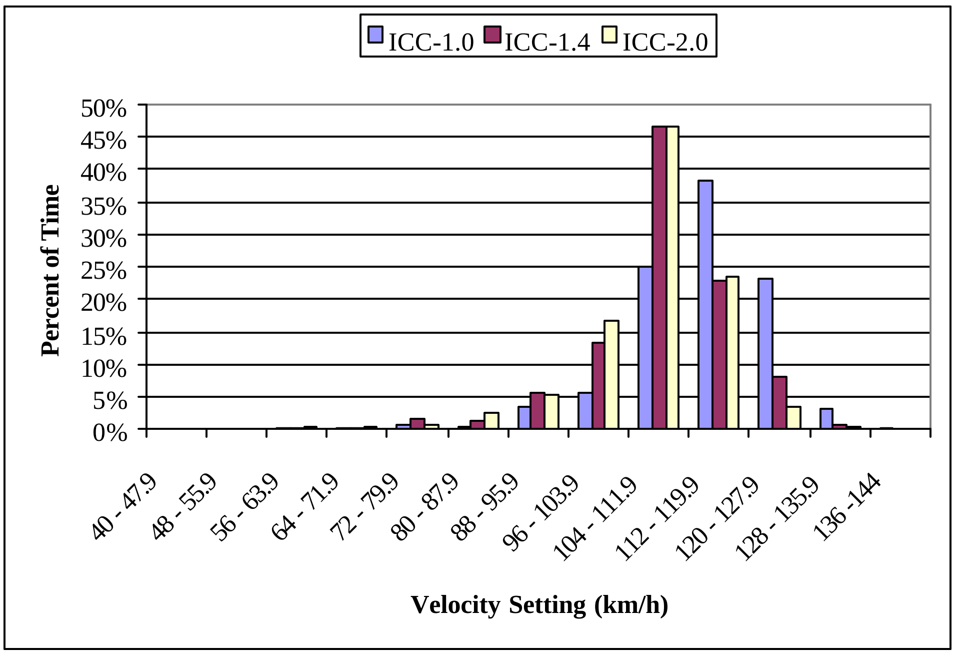

Figure 3-26 Velocity Distribution for ICC Headway Settings - Freeways

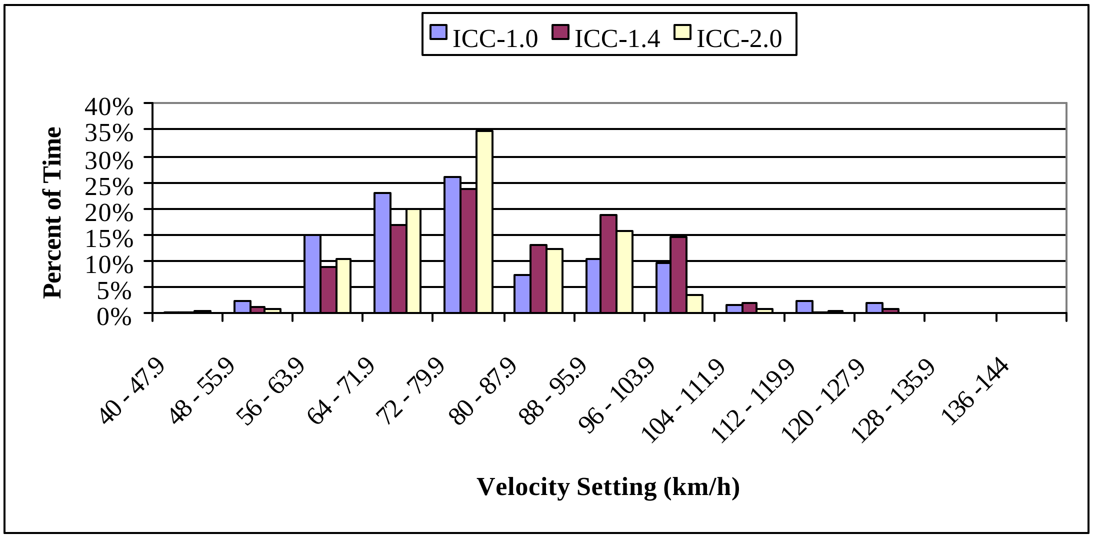

Figure 3-27 Velocity Distribution for ICC Headway Settings - Arterials

3.6.5 Usage as a Function of Headway Setting – Freeways Versus Arterials

Figure 3-28 shows the distribution of ICC headway settings on freeways and arterials for all driving. Figure 3-29 shows the same distribution for ICC driving only. Drivers use each of the ICC settings more often when it is available on freeways than they do on arterials (Figure 3-28). By contrast, when ICC is engaged, there is a tendency to use the 1.0 setting more on freeways, but the 1.4 and 2.0 second settings more on arterials (figure 3-29). Perhaps this choice, while minimal overall, reflects a desire of the driver to keep a more constant distance separation. (From above, the median set velocity on freeways for a 1.0 second headway setting is between 112-120 km/h, while on arterials, for a 2.0 second headway setting, it is between 72-80 km/h.) Another possibility is that they may just feel more comfortable with a longer headway setting on roadways where the likelihood of encountering another vehicle at a different velocity is greater.

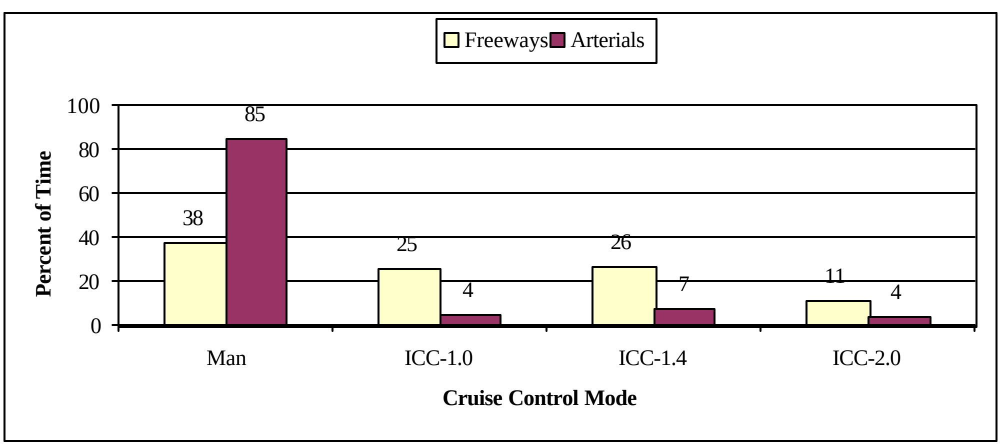

Figure 3-28 Distribution of Cruise Mode and ICC Headway Settings – All Driving – Freeways Versus Arterials

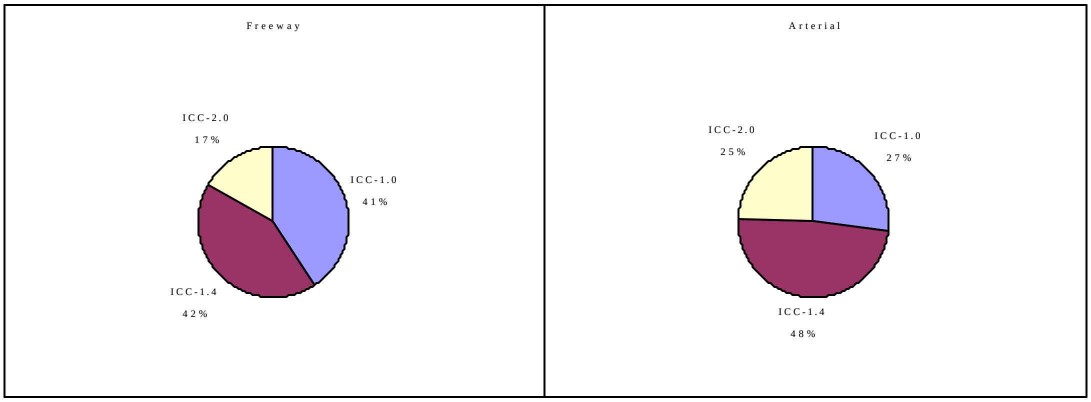

Figure 3-29 Distribution of ICC Headway Settings – Freeways Versus Arterials

3.6.6 Usage Summary

ICC was used extensively on freeways, and occasionally on arterials. On freeways and arterials, ICC was used about 50 percent more than CCC. On freeways most of the driving was during periods of light to moderate traffic, whereas on arterials, most of the driving was during periods of light traffic only. On both roadway types, ICC usage was proportionately greater compared to CCC usage for higher levels of congestion. Velocity settings were higher on freeways. Headway settings were shorter on freeways.

From an exposure standpoint, the safety effects of ICC on freeways are of greatest concern. This is not to imply that safety effects on arterials should be ignored, because level of exposure is not the sole determinant of risk. Furthermore, whereas ICC exposure on arterials is considerably less than on freeways, its use on arterials is significantly more than CCC, and arterials may pose greater safety-related demands on both the system and the driver. From the perspective of this current evaluation, when analyzing subtle changes in risk that are associated with level of exposure, freeway driving is the most likely location for observable effects.

3.7 Driving States and Transitions

This section presents the driving state and transition data. Driving states describe the type of driving situation including closing, following, separating, and cruising. Transitions describe the change from one driving state to another including the acquisition, switch, or drop of a lead vehicle. These in turn are translated into specific driving maneuvers such as lane changes and cut-ins which are more familiar terms and which commonly occur on the roadways being examined. The driving states and maneuver types are analyzed below as a function of cruise mode and road type.

3.7.1 Definition of States and Sub-States

As defined in Section 2.6.1, there are four major driving states. These are described in terms of time-headway and range-rate between the ICC vehicle and the lead vehicle. Driving state was continuously recorded. Whenever a driver changed from one state to another, a new record was created capturing the time of occurrence and its duration. The definitions of the driving states are repeated below:

Closing: driving behind another vehicle within sensor range, where the preceding vehicle was traveling at a velocity at least1.5 m/s (5 ft/s) slower than the host vehicle.

Following: driving behind another vehicle within sensor range, where the preceding vehicle velocity was within ± 1.5 m/s (5 ft/s) of the velocity of the host (ICC) vehicle.

Separating: driving behind another vehicle within sensor range, where the preceding vehicle was traveling at a velocity 1.5 m/s (5 ft/s) faster than the host vehicle.

Cruising: driving with no preceding vehicle within sensor range. For purposes of providing reliable classification of the cruising state, the sensor range was defined as that corresponding to a 2.4 second headway.

The relationship between these four major driving states is depicted in Figure 3-30.

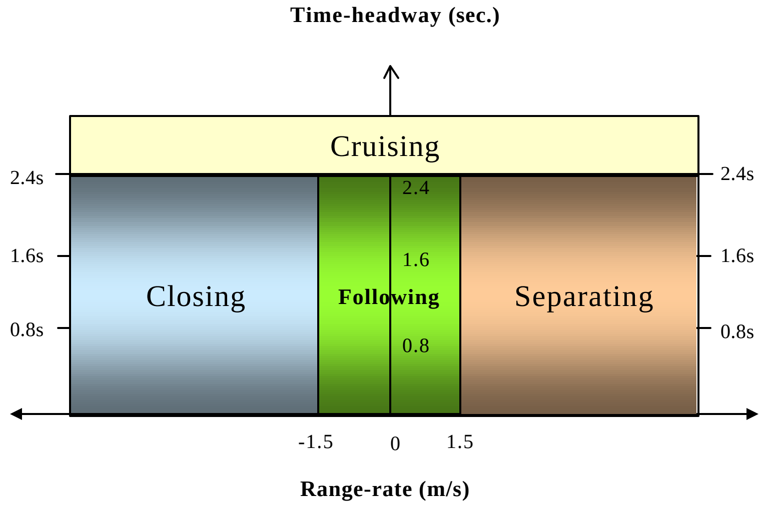

Figure 3-30 Major Driving States Represented in Terms of Time-Headway and Range Rate

The four major driving states are further divided into sub-states according to the Time-headway (THW) and Range-rate (Rdot) values given in Table 3-4. The THW values are 1.6 seconds and 0.8 second, which divide the time-headway region below 2.4 seconds into three equal parts, defined as close, middle, and far. An Rdot value of - 6 m/s is added to divide the separating and closing states into two parts each, defined as moderately and rapidly. The resulting driving sub-states can be related by their symbols as shown in Figure 3-31. The sub-states provide a finer partitioning of the time-headway versus range-rate for analysis. As indicated in the table, there are a total of 16 sub-states.

Table 3-4 Definition of Sub-States with respect to the Driving States

Driving States	Sub-States	Symbol	Definition
Closing	Close Rapidly	(CCR)	THW<=0.8s, Rdot<=-6m/s
	Close Moderately	(CCM)	THW<=0.8s, Rdot between –1.5m/s & -6m/s
	Middle Rapidly	(CMR)	THW between 0.8s & 1.6s, Rdot<=-6m/s
	Middle Moderately	(CMM)	THW between 0.8s & 1.6s, Rdot between –1.5m/s & -6m/s
	Far Rapidly	(CFR)	THW between 1.6s & 2.4s, Rdot<=-6m/s
	Far Moderately	(CFM)	THW between 1.6s & 2.4s, Rdot between –1.5m/s & -6m/s
Following	Close	(FC)	THW<=0.8s, Rdot between 1.5m/s & –1.5m/s
	Middle	(FM)	THW between 0.8s & 1.6s, Rdot between 1.5m/s & -1.5m/s
	Far	(FF)	THW between 1.6s & 2.4s, Rdot between 1.5m/s & -1.5m/s
Separating	Close Rapidly	(SCR)	THW<=0.8s, Rdot >=6m/s
	Close Moderately	(SCM)	THW<=0.8s, Rdot between 1.5m/s & 6m/s
	Middle Rapidly	(SMR)	THW between 0.8s & 1.6s, Rdot >=6m/s
	Middle Moderately	(SMM)	THW between 0.8s & 1.6s, Rdot between 1.5m/s & 6m/s
	Far Rapidly	(SFR)	THW between 1.6s & 2.4s, Rdot >=6m/s
	Far Moderately	(SFM)	THW between 1.6s & 2.4s, Rdot between 1.5m/s & 6m/s
Cruising	Cruise	(CRS)	THW>2.4s

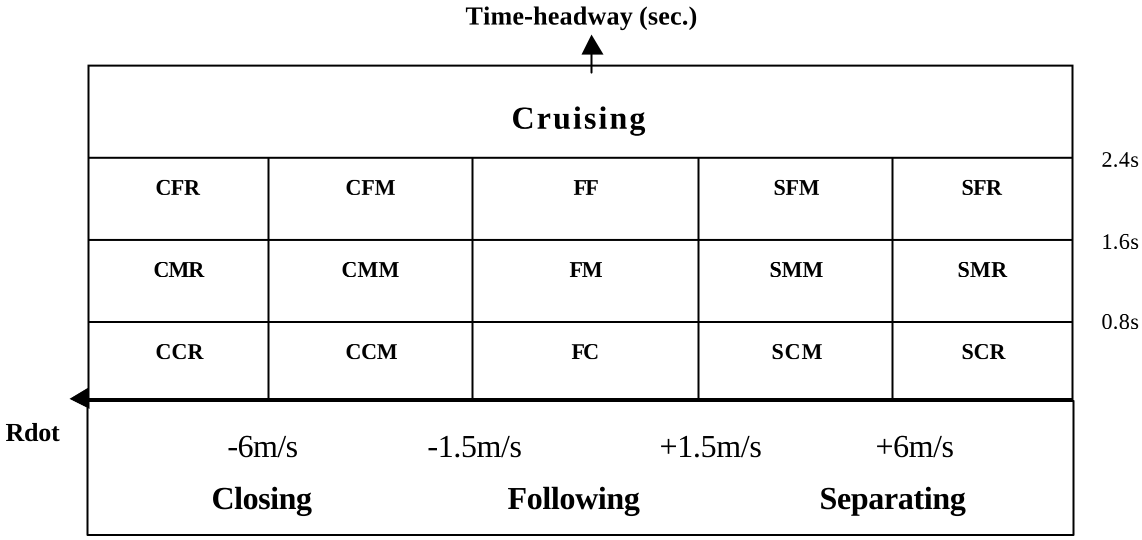

Figure 3-31 Driving Sub-States Represented in Terms of Time-headway and Range Rate

3.7.2 Definition of Transitions

Transitions describe the change from one state to another. The definitions of the transitions from Section 2.6.1 are repeated below.

Target Acquisition: defined as a change from cruising to one of the other driving states.

Target Switch: defined as a transition from following one preceding vehicle to following another. The change in preceding vehicles was defined algorithmically as an instantaneous (one deci-second to the next) change in range to the preceding vehicle greater than or equal to 1.5 m, or an instantaneous change in preceding velocity greater than or equal to 7.6 m/s.

Target Drop: defined as a change to cruising from one of the other driving states.

Acceleration: defined as a relative acceleration between the target and host vehicles leading to a change in state.

Target acquisitions, drops, and switches were subdivided into *active* and *passive.* An active transition was defined as a transition that resulted from a lane movement by the host vehicle. Transitions that were not classified as active were classified as passive, and were presumed to have resulted because of the actions of other drivers.

3.7.3 Definition of Maneuvers

The definitions of two types of maneuvers examined in this study are as follows:

Lane Change: host vehicle *actively* acquires a lead vehicle, drops a lead vehicle, or switches from one lead vehicle to another.

Cut-in: host vehicle *passively* acquires a lead vehicle, or switches from one lead vehicle to another.

3.7.4 Driving States and Sub-States - All Modes

Figure 3-32 shows the duration of the four major states separately on all roads, on classified roads only, on freeways and on arterials. The distribution pattern for the classified roads and all roads was similar with 59-64 percent of the time attributed to cruising. On freeways, 52 percent of the time was spent in the cruising mode while 37 percent of the time was spent in the following mode. This contrasts with arterial driving where 65 percent of the time was spent in the cruising mode and 28 percent of the time was spent in the following mode. Part of this difference is explained by the usage data which showed lower velocities on arterials and more driving with light traffic. The lower velocities on arterials combined with the 2.4 second time-headway limit criterion for cruising will result in more situations being classified as cruising on arteries than on freeways for the same distribution of following distances. Perhaps the main point from Figure 3-32 is the consistent and low percent of time spent in the closing mode (five-six percent). In this study closing is considered a safety-critical driving situation, and performance measures while in this mode are further examined in Section 3.8.

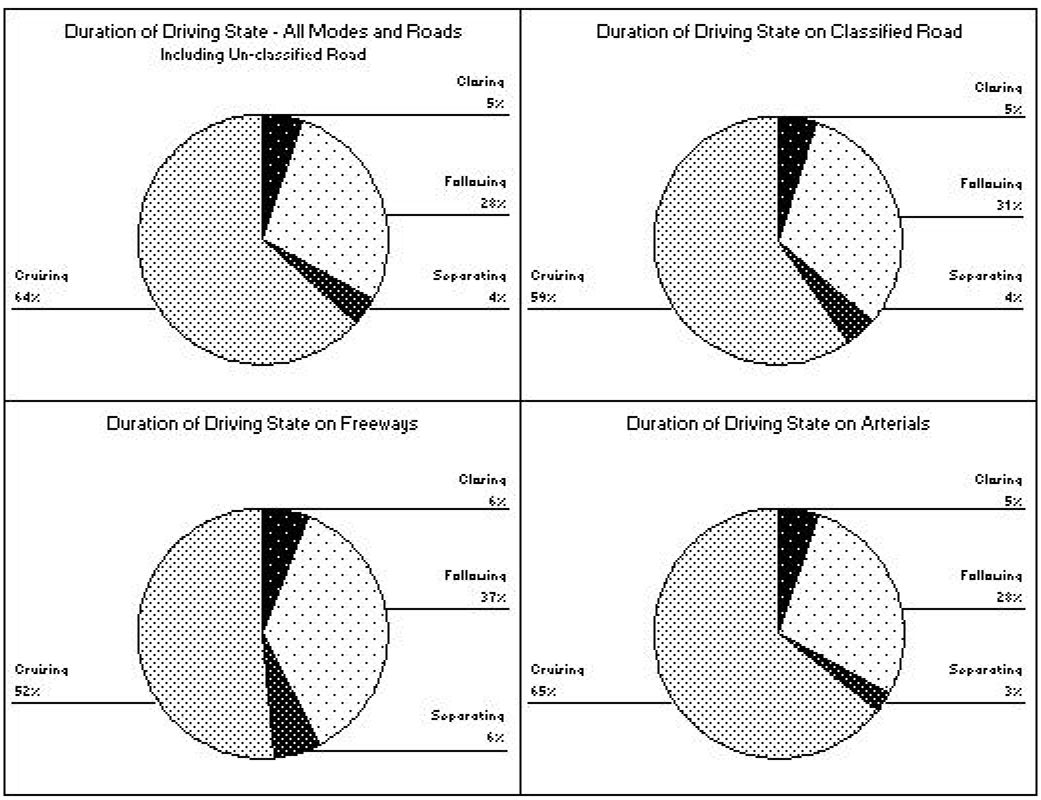

Figure 3-32 Duration of the Main Driving States – All Roads, Classified Roads, Freeways, and Arterials

Table 3-5 shows the distributions of the 16 sub-states for freeways and arterials. Figures 3-33 and 3-34 show the same data represented in the Time-Headway-Versus-Range-Rate diagrams. Drivers spent the least amount of time in the closing-close-rapidly and separating-close-rapidly sub-states on both freeways and arterials. It is interesting that the percentages for these two sub-states were about the same for freeways and arterials. It is further interesting to note that the consistent pattern between closing and separating holds for all sub-states on both freeways and arterials, but particularly freeways. Following-close occurred 7.4 percent of the time an freeways, but only 2.3 percent of the time on arterials.

Table 3-5 Distribution of Driving Sub-States on Freeways and Arterials

Distribution of Driving Sub-state - Freeways or Arterials
Based on Total Duration (hrs.) w/i Road-type

	RoadClass			
	Freeways		Arterials	
	Sum (hrs.)	Col Sum %	Sum (hrs.)	Col Sum %
Closing CR	.029431	.0%	.004219	.0%
Closing CM	2.585158	.5%	.587239	.2%
Closing MR	.224739	.0%	.153786	.0%
Closing MM	12.697856	2.6%	6.365053	1.8%
Closing FR	.591833	.1%	.577353	.2%
Closing FM	13.539953	2.7%	8.550578	2.4%
Following C	36.744200	7.4%	8.294908	2.3%
Following M	98.649706	19.8%	55.171606	15.5%
Following F	46.867153	9.4%	36.430519	10.2%
Separating CR	.024742	.0%	.	.
Separating CM	2.549881	.5%	.135389	.0%
Separating MR	.344731	.1%	.026956	.0%
Separating MM	12.471214	2.5%	3.205939	.9%
Separating FR	.485442	.1%	.049550	.0%
Separating FM	13.035092	2.6%	6.234883	1.7%
Cruising	257.0495	51.6%	231.0128	64.7%
Total	497.8906	100.0%	356.8007	100.0%

Time-headway (sec.)

Cruising 51.6%					
CFR 0.1%	CFM 2.7%	FF 9.4%	SFM 2.6 %	SFR 0.1%	2.4s
CMR 0.0%	CMM 2.6%	FM 19.8%	SMM 2.5 %	SMR 0.1%	1.6s
CCR 0.0%	CCM 0.5%	FC 7.4%	SCM 0.5%	SCR 0.0%	0.8s

Rdot

-6m/s	-1.5m/s	+1.5m/s	+6m/s

Closing | **Following** | **Separating**

Figure 3-33 Driving Sub-States Data for Freeways Represented in Terms of Time-headway and Range Rate

Time-headway (sec.)

Cruising 64.7%					
CFR 0.2%	CFM 2.4%	FF 10.2%	SFM 1.7%	SFR 0.0%	2.4s
CMR 0.0%	CMM 1.8%	FM 15.5%	SMM 0.9%	SMR 0.0%	1.6s
CCR 0.0%	CCM 0.2%	FC 2.3%	SCM 0.0%	SCR 0.0%	0.8s

Rdot

-6m/s	-1.5m/s	+1.5m/s	+6m/s

Closing | **Following** | **Separating**

Figure 3-34 Driving Sub-State Data for Arterials Represented in Terms of Time-headway and Range Rate

Figure 3-35 shows the average duration in seconds for each of the main states on classified roads When looking at the average duration of driving states, cruising states, as expected, lasted the longest time, about 40 seconds before changing to another state. The average duration of the following state was next longest, about nine seconds, while the average duration for the closing and separating states were about three seconds.

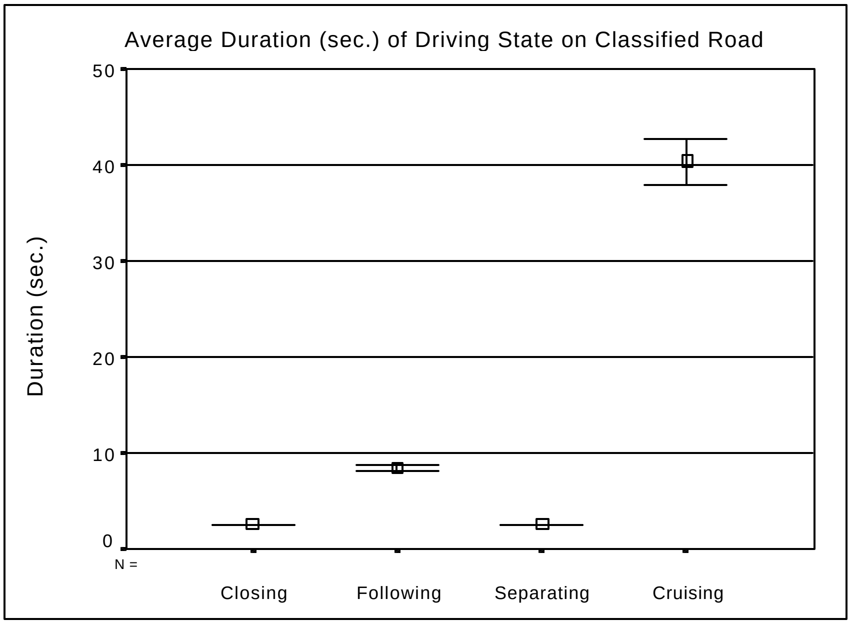

Figure 3-35 Average Duration of Driving States – Classified Roads

3.7.5 Driving States and Sub-States by Mode on Freeways

In this section the resulting data on driving states and sub-states are represented in terms of relative time distribution by mode. Table 3-6 shows the distributions of the four main states by mode and Table 3-7 shows the same information with the ICC headway settings added. For reference, Table 3-8 shows the total duration of the driving states in hours by mode and headway setting. As noted above, all the modes spent the least amount of time in the closing state. About five percent of the time was spent in the closing state for both ICC and CCC compared to 6.8 percent for manual. Since the closing state is considered the most safety critical, these results indicate an overall slight safety benefit for ICC relative to manual driving.

Table 3-6 Distribution of Four Main States by Mode on Freeways

Duration Distribution of Driving States on Freeways by Mode
Based on Total Duration by Mode; ICCs Combined

	Mode			Total
	Manual	CCC	ICC	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %
Closing	6.8%	5.2%	5.1%	6.0%
Following	43.3%	18.0%	33.9%	36.6%
Separating	5.1%	7.0%	6.4%	5.8%
Cruising	44.8%	69.8%	54.6%	51.6%
Group Total	100.0%	100.0%	100.0%	100.0%

Table 3-7 Distribution of Four Main States by Mode and Headway Setting on Freeways

Duration Distribution of Driving States on Freeways by Mode
Based on Total Duration by Mode

	Mode					Total
	Manual	CCC	ICC at 1sec.	ICC at 1.4sec	ICC at 2sec.	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %
Closing	6.8%	5.2%	7.2%	4.2%	2.4%	6.0%
Following	43.3%	18.0%	38.5%	31.6%	29.4%	36.6%
Separating	5.1%	7.0%	5.2%	6.7%	8.2%	5.8%
Cruising	44.8%	69.8%	49.1%	57.5%	60.0%	51.6%
Group Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 3-8 Total Duration of Driving States by Mode and Headway Setting – Freeways

	Duration (Hours)
Manual	250.5
CCC	64.3
ICC at 1 sec.	72.4
ICC at 1.4 sec.	79.4
ICC at 2.0 sec.	31.4
Total ICC	183.2
Total All Modes	498.0

Compared to manual driving, ICC spent more time in cruising, 54.6 percent versus 44.8 percent, and less time in following, 33.9 percent versus 43.3 percent. This is consistent with the observation that ICC was used more often than manual in light traffic where there are more opportunities for cruising (time headway greater than 2.4 seconds) to occur. It is also consistent with the observation that the average velocity with ICC was greater than that with manual. In the cruising state, which includes no traffic, there are more opportunities to travel faster. The percent of time that there was no traffic (beyond the physical sensor range) for ICC was 41 compared to 31 for manual. It should be pointed out that the finding of higher velocities and more cruising may seem to be counterintuitive in the sense that, with fixed traffic conditions, one would expect more closings with higher velocities. Apparently, this effect is more than offset by the fact that more time is spent by ICC with no traffic present.

Relative to CCC, ICC spent less time in cruising, 54.6 percent versus 69.8 percent, and more time in following, 33.9 percent versus 18.0 percent. This is consistent with the observation that ICC was used more often than CCC in moderate traffic and heavy traffic where there are more opportunities for non-cruising to occur. It also indicates that drivers were relying on the ICC system to maintain headways in the following state for significant periods of time.

As indicated in Table 3-7, shorter ICC headway settings were associated with more time spent in the closing and following states and less time in the cruising states. For the ICC headway setting of 1.0 seconds, 7.2 percent of the time was spent in the closing state compared to only 2.4 percent when the headway setting was 2.0 seconds. This result is consistent with the concept that shorter headways will result in more opportunities for non-cruising states. From a safety perspective, driving at the 2.0 second headway setting appears to be safer than the 1.0 second headway setting in terms of significantly less time spent in closing (more safety-critical) and more time in cruising (more safety-benign). It is interesting to note that ICC driving with the 1.0 second headway setting had a similar state distribution as manual driving.

Another notable difference in driving states between the 1.0 and 2.0 second ICC headway settings is that the time spent in cruising was significantly more for the longer headway (49.1 percent for 1.0 second versus 60.0 percent for 2.0 seconds), and the time spent in following was significantly less for the longer headway (38.5 percent for 1.0 second versus 29.4 percent for 2.0 seconds) . These results are consistent with the observation that the 2.0 second drivers were predominantly older drivers who had longer headways, and may have chosen to use the ICC more often in light traffic and when no traffic was present.

Table 3-9 shows the distributions of the sub-states by mode and Table 3-10 shows the same information with the ICC headway settings added. The closing-close-rapidly sub-state, the most safety-critical state, showed 0.0 percent for all modes. ICC in general spent less percent time in the closing sub-states compared to the manual and CCC modes. The only exception to this is that ICC spent slightly more time in the closing-far-moderately sub-state. This is a safety positive result for ICC since this sub-state is the most safety-benign of the closing substates.

ICC spent substantially less time (1.7 percent) in the more safety-critical sub-state of following-close, compared to both manual (12.8 percent) and CCC (2.5 percent). Also, ICC spent proportionately more time than manual and CCC in the more safety-benign sub-state of following-far. As noted above and shown in Tables 3-6 and 3-8, ICC generally spent more time in the following states than CCC because of its ability to maintain headways in moderate and heavy traffic.

Table 3-9 Distribution of Sub-States by Mode on Freeways

Duration Distribution of Driving Sub-states on Freeways by Mode
Based on Total Duration by Mode; ICCs Combined

	Mode			Total
	Manual	CCC	ICC	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %
ClsCR	.0%	.0%	.0%	.0%
ClsCM	.8%	.4%	.2%	.5%
ClsMR	.1%	.0%	.0%	.0%
ClsMM	3.1%	2.2%	2.0%	2.6%
ClsFR	.1%	.1%	.1%	.1%
ClsFM	2.7%	2.6%	2.8%	2.7%
FolC	12.8%	2.5%	1.7%	7.4%
FolM	22.0%	8.5%	20.8%	19.8%
FolF	8.6%	7.0%	11.4%	9.4%
SepCR	.0%	.0%	.0%	.0%
SepCM	.5%	.5%	.5%	.5%
SepMR	.0%	.1%	.1%	.1%
SepMM	2.3%	2.7%	2.7%	2.5%
SepFR	.1%	.2%	.1%	.1%
SepFM	2.2%	3.5%	2.9%	2.6%
Cruis.	44.8%	69.8%	54.6%	51.6%
Group Total	100.0%	100.0%	100.0%	100.0%

As previously discussed and further illustrated in Table 3-9, the ICC system was driven more in the cruising state than manual because of its greater use in light traffic. In contrast, it spent less time in the cruising state than CCC because it was used more often than CCC in moderate traffic and heavy traffic.

Table 3-10 further shows that the 1.0 second ICC headway setting produced a state distribution similar to manual driving with a notable exception in the following states discussed below. The 1.4 and 2.0 second ICC headway settings resulted in more safety benign distributions of driving states than the 1.0 second setting; i.e., less time was spent in closing and more time was spent in the other states.

Within the closing states, the 1.0 second ICC headway setting spent slightly more time in the closing-middle-moderate, closing-far-rapid, and closing-far-moderate states than manual or CCC. However, the 1.0 second ICC headway setting spent less time than manual or CCC in the most critical closing-close substates. The 1.4 second ICC headway setting generally spent less time in all closing states than manual or CCC with the exception of slightly more time in the most benign closing sub-state of closing-far-moderate. The 2.0 second ICC headway setting spent significantly less time in all closing states than manual or CCC.

When comparing ICC to manual for the following states, there is interesting evidence that the ICC system functioned well in maintaining the set headways. Note that the 1.0 and 1.4 second headway settings resulted in most time being spent in the following-middle sub-state which is defined as headways between 0.8 and 1.6 seconds, an interval that spans the settings in question. Also note that the 2.0 second headway setting resulted in most time being spent in the following-far sub-state, defined as headways between 1.6 and 2.4 seconds; again, an interval that includes the 2.0 second headway.

Table 3-10 Distribution of Sub-States by Mode and Headway Setting on Freeways

Duration Distribution of Driving Sub-states on Based on Total Duration

	Mode					Total
	Manual	CCC	ICC at 1sec.	ICC at 1.4sec	ICC at 2sec.	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %
ClsC	.0	.0	.0	.0	.0	.0
ClsC	.8	.4	.3	.1	.0	.5
ClsM	.1	.0	.0	.0	.0	.0
ClsM	3.1	2.2	3.4	1.3	.4	2.6
ClsF	.1	.1	.2	.1	.0	.1
ClsF	2.7	2.6	3.3	2.8	1.9	2.7
Fol	12.8	2.5	3.0	1.0	.3	7.4
Fol	22.0	8.5	28.8	21.1	1.7	19.8
Fol	8.6	7.0	6.7	9.4	27.5	9.4
SepC	.0	.0	.0	.0	.0	.0
SepC	.5	.5	.5	.5	.4	.5
SepM	.0	.1	.1	.1	.1	.1
SepM	2.3	2.7	2.3	2.9	3.1	2.5
SepF	.1	.2	.1	.1	.2	.1
SepF	2.2	3.5	2.2	3.1	4.3	2.6
Crui	44.8	69.8	49.1	57.5	60.0	51.6
Group	100.0	100.0	100.0	100.0	100.0	100.0

Summary: ICC in general spent less time in the closing state and close sub-states compared to the manual and CCC modes. Since the closing state and close sub-states are considered the most safety-critical, these results indicate an overall slight safety benefit for ICC relative to CCC and manual driving.

3.7.6 Driving States and Sub-States by Mode on Arterials

Table 3-11 shows the distributions of the four main states by mode and Table 3-12 shows the same information with the ICC headway settings added. For reference, Table 3-13 shows the total duration of the driving states in hours by mode and headway setting. The ICC system spent proportionately more time in the closing (8.5 percent) and following (39.5 percent) states, and less time in the cruising state (48.3 percent) than either manual or CCC. However, virtually no ICC closing events were in the most safety critical sub-state of closing-close-rapidly. More time in the closing states is a safety concern for the ICC system on arterials which is consistent with other safety performance measures investigated (it is pointed out in Section 3.9.2.1.7, for example, that close calls exhibited unusual characteristics on arterials in comparison to freeways.) However, the results contrast with the observation, discussed in Section 3.9.2.1.1, that the average closing rates are about the same for ICC and manual, and highest for CCC. Although there is a concern for the ICC system on arterials it is tempered by several factors.

1. The ICC system was used only 6 percent of the time on arterials for a total of less than 14 hours and, while on arterials, only 8.5 percent of the time was in the closing state. Overall, therefore, ICC drivers experienced closing states on arterials only about 0.5 percent of the time.
2. There are unique arterial roadway conditions such as more speed restrictions (e.g., intersections, traffic control devices, roadway geometries), fewer lanes, and fewer opportunities for passing, which introduce confounding factors not controlled for in the analysis.
3. Finally, there is the matter of computation. In this report, the driver is the unit of analysis. However, when contrasting these results with an averaging method, it was found that the averaging method produced more intuitive results. Namely, ICC had more cruising and less following and closing than manual. Apparently, the sparsity of data when disaggregating into finer components is influencing the outcome. The net result seems to be that with very little data on arterials, the current results should be treated as unreliable.

Because of the above, the observed pattern of ICC and CCC driving states on arterials may be somewhat unique and not generally representative (the CCC system was used for a total of only 3 hours). The remainder of this section describes further data on arterials but does not attempt to interpret the results.

Table 3-11 Distribution of Four Main States by Mode on Arterials

Duration Distribution of Driving States on Arterials by Mode
Based on Total Duration by Mode; ICCs Combined

	Mode			Total
	Manual	CCC	ICC	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %
Closing	4.4%	6.5%	8.5%	4.6%
Following	27.6%	15.3%	39.5%	28.0%
Separating	2.7%	4.6%	3.6%	2.7%
Cruising	65.3%	73.7%	48.3%	64.7%
Group Total	100.0%	100.0%	100.0%	100.0%

Table 3-12 Distribution of Four Main States by Mode and Headway Setting on Arterials

Duration Distribution of Driving States on Arterials by Mode
Based on Total Duration by Mode

	Mode					Total
	Manual	CCC	ICC at 1sec.	ICC at 1.4sec	ICC at 2sec.	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %
Closing	4.4%	6.5%	8.4%	9.2%	7.9%	4.6%
Following	27.6%	15.3%	40.8%	40.4%	36.6%	28.0%
Separating	2.7%	4.6%	3.7%	3.3%	4.0%	2.7%
Cruising	65.3%	73.7%	47.1%	47.1%	51.5%	64.7%
Group Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 3-13 Total Duration of Driving States by Mode and Headway Setting – Arterials

	Duration (Hours)
Manual	339.9
CCC	3.0
ICC at 1 sec.	4.9
ICC at 1.4 sec.	5.2
ICC at 2.0 sec.	3.7
Total ICC	13.8
Total All Modes	356.7

From Table 3-12, there were very little differences in the distributions of the four main states for each of the ICC headway settings. The 2.0 second headway setting had slightly more time in the cruising state and less time in the closing and following states, as would be expected.

Table 3-14 shows the distributions of the sub-states by mode and Table 3-15 shows the distributions of the sub-states by cruise mode and ICC headway setting. There were very little differences in percentages between the modes for the closing-close-rapidly, closing-close-moderately, closing-close-rapidly, and closing-far-rapidly sub-states. The closing-middle-moderately, and closing-far moderately sub-states had higher percentages for ICC compared to both CCC and manual. Following-close was highest for manual, while following-far was substantially higher for ICC .

Within ICC, the following-close percentage was substantially higher for the 1.0 second headway setting compared to other settings; the following-middle percentages for the 1.0 second and 1.4 second headway settings were about the same and substantially greater than the percentage for the 2.0 second headway setting; and the following-far percentage was substantially higher for the 2.0 second headway setting, compared to the other settings. The remaining percentages were about the same.

As was observed with freeway driving, there is similar evidence that the ICC system functioned well in maintaining the set headways. On arteries, the 1.0 and 1.4 second headway settings resulted in most time being spent in the following-middle sub-state which is defined as headways between 0.8 and 1.6 seconds, an interval that spans the settings in question. Also, the 2.0 second headway setting resulted in most time being spent in the following-far sub-state, defined as headways between 1.6 and 2.4 seconds; again, an interval that includes the 2.0 second headway.

Summary: The arterial results are considered unreliable for the following reasons: there was very little data available to analyze compared to freeway driving; arterials have unique roadway conditions that warrant separate analyses for each condition; and the driver-as-unit-of-analysis computation method may have produced questionable results due to the sparsity of data. Therefore, no safety effect can be determined for ICC driving on arterials from the state and sub-state data.

Table 3-14 Distribution of Sub-States by Mode on Arterials

Duration Distribution of Driving Sub-states on Arterials by Mode
Based on Total Duration by Mode; ICCs Combined

	Mode			Total
	Manual	CCC	ICC	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %
ClsCR	.0%	.	.0%	.0%
ClsCM	.2%	.1%	.2%	.2%
ClsMR	.0%	.0%	.1%	.0%
ClsMM	1.7%	2.3%	3.4%	1.8%
ClsFR	.2%	.1%	.3%	.2%
ClsFM	2.3%	3.9%	4.5%	2.4%
FolC	2.4%	1.2%	1.5%	2.3%
FolM	15.3%	6.4%	20.7%	15.5%
FolF	9.9%	7.6%	17.4%	10.2%
SepCM	.0%	.2%	.1%	.0%
SepMR	.0%	.2%	.0%	.0%
SepMM	.9%	1.4%	1.2%	.9%
SepFR	.0%	.3%	.1%	.0%
SepFM	1.7%	2.5%	2.2%	1.7%
Cruis.	65.3%	73.7%	48.3%	64.7%
Group Total	100.0%	100.0%	100.0%	100.0%

Table 3-15 Distribution of Sub-States by Mode and Headway Setting on Arterials

Duration Distribution of Driving Sub-states on Arterials by Mode
Based on Total Duration by Mode

	Mode					Total
	Manual	CCC	ICC at 1sec.	ICC at 1.4sec	ICC at 2sec.	
	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %	Col Sum %
ClsCR	.0%	.	.0%	.	.	.0%
ClsCM	.2%	.1%	.4%	.2%	.1%	.2%
ClsMR	.0%	.0%	.1%	.1%	.1%	.0%
ClsMM	1.7%	2.3%	3.8%	3.7%	2.4%	1.8%
ClsFR	.2%	.1%	.2%	.4%	.4%	.2%
ClsFM	2.3%	3.9%	3.8%	4.8%	4.9%	2.4%
FolC	2.4%	1.2%	3.5%	.3%	.3%	2.3%
FolM	15.3%	6.4%	27.2%	25.7%	4.9%	15.5%
FolF	9.9%	7.6%	10.2%	14.3%	31.4%	10.2%
SepCM	.0%	.2%	.1%	.1%	.0%	.0%
SepMR	.0%	.2%	.0%	.1%	.0%	.0%
SepMM	.9%	1.4%	1.6%	1.2%	.9%	.9%
SepFR	.0%	.3%	.0%	.1%	.1%	.0%
SepFM	1.7%	2.5%	1.9%	1.9%	3.0%	1.7%
Cruis.	65.3%	73.7%	47.1%	47.1%	51.5%	64.7%
Group Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

3.7.7 Lane Changes on Freeways

In this section the resulting lane change data on freeways are represented in terms of counts, frequency (counts as a percentage of total) and rates (counts per kilometer) as a function of cruise mode, ICC headway setting, driving states and sub-states. It should be noted that lane changes in this analysis do not include all lane changes. Those that involve no preceding vehicle, i.e., *cruise to cruise*, are generally excluded. Also excluded are those lane changes that involve a lead vehicle where the criteria for a "switch" are not met. In these cases a distinction can not be made as to whether or not there was one lead vehicle throughout the maneuver or a switch to another lead vehicle during the lane change. Although the absolute number of lane changes detected is an underestimate, the relative results between and within modes is considered valid. (See Section 2.6.1.)

It was hypothesized that, by adjusting the equipped vehicle's velocity to that of slower preceding vehicles, ICC drivers would be less likely to change lanes to go around slower vehicles and, therefore, the number of lane changes relative to manual driving would be reduced. As lane changes increase turbulence in traffic flow, and are often associated with high-accident locations on freeways (Cirillo, 1968), an ICC contribution to a reduction in lane changing would be likely to make a contribution to safety as well. National police reported crash statistics indicate that approximately four percent of crashes involve a lane change in which the driver was unaware of the presence of the vehicle in the adjacent lane (Tijerina, 1995).

The mean number of lane changes per hundred kilometers is shown in Figure 3-36 as a function of cruise control mode and ICC headway setting. It can be seen that there were significantly fewer lane changes with ICC and CCC when compared to the number of lane changes made in manual mode. The number of lane changes per hundred kilometers was reduced from approximately 19 for manual to 8 for ICC. The hypothesis that ICC would reduce the probability of a lane change (relative to the manual mode) in response to slower moving vehicles is strongly supported by this finding. If lane changes increase the probability of crashes, then ICC reduces the probability of crashes attributable to lane changes and thus provides a safety benefit. A further examination of lane change scenarios is given in Sections 3.9.2.1 and 3.9.2.2.

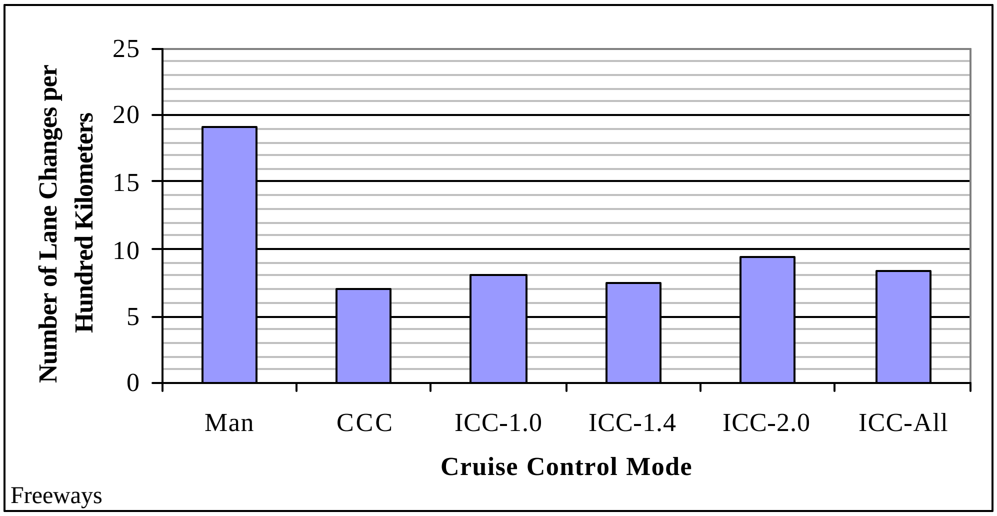

Figure 3-36 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode and ICC Headway Setting - Freeways

There were no significant lane change differences between ICC and CCC, nor between the different ICC headway settings. The fact that the lane change rate was similar between the CCC and ICC modes contrasts with other measures, such as velocity and time-headway, where the ICC means fell somewhere in between CCC and manual means. When a slower moving vehicle is encountered, the CCC driver, unlike the ICC driver, must change lanes to avoid disengaging the system. The almost equal rate of lane changes between ICC and CCC in view of the fact that ICC is used in more traffic congestion and, thus, encounters a greater number of slower vehicles, is further evidence that ICC reduces a driver's need to make lane changes.

Table 3-16 shows the total number of lane changes[2], and the number of lane changes per hundred kilometers as a function of cruise control mode and the before/after driving states. Table 3-17 shows similar data as a function of ICC headway settings. The rate of lane changes made from the closing state was substantially less with ICC compared to both manual and CCC. The lane changes made to the closing state was also substantially less with ICC compared to manual; ICC and CCC were about the same. Relative to ICC headway setting, the lowest rate of lane changes from the closing state were made with a headway setting of 2.0 seconds followed by a headway setting of 1.0 second. The lowest rate of lane changes to the closing state were made with a headway setting of 1.4 seconds followed by a headway setting of 1.0 second.

[2] The number of lane changes refers here and in the subsequent tables to the summation of lane changes over all drivers. Percentages of lane changes referred to in the text are also relative to the total number of lane changes for all drivers per mode. The rate of lane changes are calculated with the driver as the unit of analysis.

Table 3-16 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode – Freeways

Number of Lane Changes per Hundred Kilometers on Freeways
by Driving State before and after Lane Change
(ICC Combined)

Before Lane Change		After Lane Change: Closing No. of LC	Closing Rate of LC	Following No. of LC	Following Rate of LC	Separating No. of LC	Separating Rate of LC	Cruising No. of LC	Cruising Rate of LC	Total No. of LC	Total Rate of LC
Manual	Closing	196	.65	236	.83	127	.52	426	1.45	985	3.46
	Following	176	.61	615	2.62	303	1.37	698	3.10	1792	7.69
	Separating	20	.05	121	.52	187	.92	283	1.68	611	3.16
	Cruising	278	1.24	383	1.79	308	1.72	23	.06	992	4.82
	Group Total	670	2.55	1355	5.76	925	4.53	1430	6.29	4380	19.13
CCC	Closing	18	.20	21	.27	13	.10	82	1.00	134	1.57
	Following	5	.19	32	.29	15	.16	72	.98	124	1.62
	Separating	1	.03	7	.04	27	.21	58	1.04	93	1.31
	Cruising	37	.43	57	.56	53	1.43	6	.05	153	2.48
	Group Total	61	.85	117	1.16	108	1.90	218	3.07	504	6.98
ICC	Closing	43	.11	50	.14	56	.20	164	.59	313	1.04
	Following	37	.22	181	.76	174	.58	371	1.80	763	3.35
	Separating	6	.01	51	.23	119	.41	174	.99	350	1.64
	Cruising	119	.55	178	.80	170	.84	12	.05	479	2.24
	Group Total	205	.89	460	1.93	519	2.02	721	3.43	1905	8.27

Table 3-17 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode and ICC Headway Setting - Freeways

Number of Lane Changes per Hundred Kilometers on Freeways by Driving State before and after Lane Change

Before Lane Change		After Lane Change: Closing No. of LC	Closing Rate of LC	Following No. of LC	Following Rate of LC	Separating No. of LC	Separating Rate of LC	Cruising No. of LC	Cruising Rate of LC	$T Group Total No. of LC	$T Group Total Rate of LC
Manual	Closing	196	.65	236	.83	127	.52	426	1.45	985	3.46
	Following	176	.61	615	2.62	303	1.37	698	3.10	1792	7.69
	Separating	20	.05	121	.52	187	.92	283	1.68	611	3.16
	Cruising	278	1.24	383	1.79	308	1.72	23	.06	992	4.82
	Group Total	670	2.55	1355	5.76	925	4.53	1430	6.29	4380	19.13
CCC	Closing	18	.20	21	.27	13	.10	82	1.00	134	1.57
	Following	5	.19	32	.29	15	.16	72	.98	124	1.62
	Separating	1	.03	7	.04	27	.21	58	1.04	93	1.31
	Cruising	37	.43	57	.56	53	1.43	6	.05	153	2.48
	Group Total	61	.85	117	1.16	108	1.90	218	3.07	504	6.98
ICC at 1sec.	Closing	24	.13	29	.22	30	.19	91	.57	174	1.10
	Following	15	.15	93	1.03	91	.85	165	1.72	364	3.75
	Separating	4	.03	21	.31	44	.41	50	.54	119	1.28
	Cruising	55	.67	67	.68	52	.63	6	.02	180	2.00
	Group Total	98	.97	210	2.23	217	2.08	312	2.84	837	8.12
ICC at 1.4sec	Closing	15	.14	18	.11	22	.27	61	.82	116	1.33
	Following	16	.20	60	.44	63	.50	148	1.71	287	2.84
	Separating	2	.01	20	.20	53	.38	81	.70	156	1.29
	Cruising	40	.30	77	.76	86	.89	5	.12	208	2.07
	Group Total	73	.64	175	1.51	224	2.03	295	3.35	767	7.53
ICC at 2sec.	Closing	4	.05	3	.09	4	.12	12	.29	23	.55
	Following	6	.33	28	.86	20	.34	58	2.03	112	3.57
	Separating	.	.	10	.18	22	.45	43	1.95	75	2.57
	Cruising	24	.77	34	1.00	32	1.02	1	.00	91	2.79
	Group Total	34	1.15	75	2.14	78	1.93	114	4.27	301	9.49

Tables 3-18 through 3-21 show, respectively, the number of lane changes as a function of cruise control mode and the before/after driving sub-states (16x16 matrices); the number of lane changes as a function of cruise control mode, ICC headway setting and the before/after driving sub-states; the number of lane changes per hundred kilometers as a function of cruise control mode and the before/after driving sub-states; and the number of lane changes per hundred kilometers as a function of cruise control mode, ICC headway setting and the before/after driving sub-states.

Table 3-18 Number of Lane Changes as a Function of Cruise Control Mode and the Before/After Driving Sub-States - Freeways

Number of Lane Changes on Freeways
by Driving sub-state before and after Lane Change
(ICC Combined)

Before Lane Change		After Lane Change																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
Manual	ClsCR	.	.	.	4	.	.	7	1	.	.	1	.	.	.	.	5	18
	ClsCM	1	14	2	16	4	13	65	27	16	3	30	6	16	.	11	167	391
	ClsMR	2	3	3	1	.	.	.	4	.	.	1	.	1	.	.	15	30
	ClsMM	1	20	1	31	3	17	23	46	13	.	14	2	21	1	7	137	337
	ClsFR	.	.	4	.	3	4	1	2	1	.	.	.	.	.	1	12	28
	ClsFM	.	4	.	24	1	20	3	9	18	.	1	.	3	1	7	90	181
	FolC	3	33	.	25	3	13	90	73	34	1	68	8	61	2	16	204	634
	FolM	1	18	.	26	.	13	85	125	44	1	37	3	46	2	25	229	655
	FolF	.	2	.	13	2	24	39	33	92	.	6	1	12	2	12	265	503
	SepCR	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1
	SepCM	.	.	.	2	.	.	14	6	3	.	3	1	7	.	1	7	44
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	2	3
	SepMM	.	4	.	3	.	3	29	21	6	1	53	1	12	2	22	47	204
	SepFR	.	.	.	.	.	.	.	.	.	1	2	.	1	.	1	12	17
	SepFM	.	.	.	5	.	3	18	10	14	2	37	.	19	3	16	215	342
	Cruis.	1	8	2	41	21	205	79	98	206	5	93	21	95	4	90	23	992
	Group Total	9	106	12	191	37	315	453	455	447	14	346	43	295	17	210	1430	4380
CCC	ClsCR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	2
	ClsCM	.	.	.	1	.	.	1	3	1	.	4	.	2	.	1	26	39
	ClsMR	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	1	2
	ClsMM	.	3	.	5	1	.	2	6	4	.	1	.	4	.	.	26	52
	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	4
	ClsFM	.	.	.	2	.	6	.	.	3	.	.	.	1	.	.	23	35
	FolC	.	.	.	.	.	.	.	1	3	.	4	.	1	.	.	16	25
	FolM	.	.	.	1	1	.	5	5	1	.	2	.	2	.	1	26	44
	FolF	.	.	.	.	.	3	4	6	7	.	1	.	1	.	3	30	55
	SepCM	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	4
	SepMM	.	.	.	.	.	1	.	.	2	.	4	.	2	.	4	5	18
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6	6
	SepFM	.	.	.	.	.	.	1	2	2	.	3	.	5	1	4	47	65
	Cruis.	.	.	.	4	3	30	7	17	33	1	17	1	14	1	19	6	153
	Group Total	.	3	.	13	5	40	20	40	57	1	36	1	36	2	32	218	504
ICC Combined	ClsCM	.	2	.	2	.	3	5	2	2	.	3	.	1	1	3	13	37
	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	2
	ClsMM	.	4	.	10	.	.	2	9	4	.	7	1	11	1	8	70	127
	ClsFR	.	.	.	.	1	2	.	1	.	.	.	.	2	.	1	11	18
	ClsFM	.	1	.	7	.	11	3	12	10	.	5	.	7	1	4	68	129
	FolC	.	.	.	1	.	.	6	6	2	1	9	4	11	.	5	23	68
	FolM	.	4	.	7	.	8	18	60	16	.	28	13	38	5	30	188	415
	FolF	.	1	.	6	.	10	4	7	62	1	4	2	10	1	12	160	280
	SepCR	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	SepCM	.	.	.	1	.	.	2	3	1	.	1	.	11	.	.	6	25
	SepMR	.	.	.	.	.	.	.	.	.	.	1	.	1	2	.	1	5
	SepMM	.	1	.	1	.	1	5	8	6	1	34	1	6	.	7	23	94
	SepFR	.	.	.	.	.	.	.	.	2	.	2	2	1	1	.	20	28
	SepFM	.	.	.	.	.	2	4	9	11	.	25	2	6	.	14	124	197
	Cruis.	.	4	.	14	4	97	18	50	110	4	61	6	51	2	46	12	479
	Group Total	.	17	.	49	5	134	67	167	226	7	181	31	156	14	130	721	1905

Table 3-19 Number of Lane Changes as a Function of Cruise Control Mode, ICC Headway Settings and the Before/After Driving Sub-States – Freeways

Number of Lane Changes on Freeways
by Driving Sub-state before and after Lane Change

Before Lane change		After Lane Change																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
Manual	ClsCR	.	.	.	4	.	.	7	1	.	.	1	.	.	.	.	5	18
	ClsCM	1	14	2	16	4	13	65	27	16	3	30	6	16	.	11	167	391
	ClsMR	2	3	3	1	.	.	.	4	.	.	1	.	1	.	.	15	30
	ClsMM	1	20	1	31	3	17	23	46	13	.	14	2	21	1	7	137	337
	ClsFR	.	.	4	.	3	4	1	2	1	.	.	.	.	.	1	12	28
	ClsFM	.	4	.	24	1	20	3	9	18	.	1	.	3	1	7	90	181
	FolC	3	33	.	25	3	13	90	73	34	1	68	8	61	2	16	204	634
	FolM	1	18	.	26	.	13	85	125	44	1	37	3	46	2	25	229	655
	FolF	.	2	.	13	2	24	39	33	92	.	6	1	12	2	12	265	503
	SepCR	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1
	SepCM	.	.	.	2	.	.	14	6	3	.	3	1	7	.	1	7	44
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	2	3
	SepMM	.	4	.	3	.	3	29	21	6	1	53	1	12	2	22	47	204
	SepFR	.	.	.	.	.	.	.	.	.	1	2	.	1	.	1	12	17
	SepFM	.	.	.	5	.	3	18	10	14	2	37	.	19	3	16	215	342
	Cruis.	1	8	2	41	21	205	79	98	206	5	93	21	95	4	90	23	992
	Group Total	9	106	12	191	37	315	453	455	447	14	346	43	295	17	210	1430	4380
CCC	ClsCR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	2
	ClsCM	.	.	.	1	.	.	1	3	1	.	4	.	2	.	1	26	39
	ClsMR	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	1	2
	ClsMM	.	3	.	5	1	.	2	6	4	.	1	.	4	.	.	26	52
	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	4
	ClsFM	.	.	.	2	.	6	.	.	3	.	.	.	1	.	.	23	35
	FolC	.	.	.	.	.	.	.	1	3	.	4	.	1	.	.	16	25
	FolM	.	.	.	1	1	.	5	5	1	.	2	.	2	.	1	26	44
	FolF	.	.	.	.	.	3	4	6	7	.	1	.	1	.	3	30	55
	SepCM	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	4
	SepMM	.	.	.	.	.	1	.	.	2	.	4	.	2	.	4	5	18
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6	6
	SepFM	.	.	.	.	.	.	1	2	2	.	3	.	5	1	4	47	65
	Cruis.	.	.	.	4	3	30	7	17	33	1	17	1	14	1	19	6	153
	Group Total	.	3	.	13	5	40	20	40	57	1	36	1	36	2	32	218	504
ICC at 1sec.	ClsCM	.	1	.	1	.	3	1	2	1	.	2	.	1	1	2	8	23
	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	2
	ClsMM	.	4	.	5	.	.	2	6	4	.	5	.	7	.	4	43	80
	ClsFR	.	.	.	.	.	1	.	1	.	.	.	.	2	.	.	9	13
	ClsFM	.	1	.	4	.	4	2	6	4	.	2	.	3	.	1	29	56
	FolC	.	.	.	1	.	.	4	6	1	1	6	4	7	.	5	13	48
	FolM	.	4	.	1	.	5	12	33	12	.	24	6	20	1	11	96	225
	FolF	.	.	.	1	.	3	1	4	20	.	2	.	1	1	2	56	91
	SepCM	.	.	.	1	.	.	1	2	1	.	1	.	5	.	.	3	14
	SepMR	.	.	.	.	.	.	.	.	.	.	1	.	1	1	.	1	4
	SepMM	.	1	.	.	.	1	3	5	2	1	15	.	.	.	1	7	36
	SepFR	.	.	.	.	.	.	.	.	1	.	.	.	.	1	.	5	7
	SepFM	.	.	.	.	.	1	3	1	2	.	10	.	2	.	5	34	58
	Cruis.	.	4	.	6	4	41	7	21	39	.	19	1	15	1	16	6	180
	Group Total	.	15	.	20	4	59	36	87	87	2	87	11	64	6	47	312	837
ICC at 1.4sec	ClsCM	.	1	.	1	.	.	2	.	1	.	.	.	.	.	1	4	10
	ClsMM	.	.	.	4	.	.	.	3	.	.	2	1	4	1	4	25	44
	ClsFR	.	.	.	.	1	1	.	.	.	.	.	.	.	.	1	2	5
	ClsFM	.	.	.	2	.	5	1	6	5	.	2	.	3	.	3	30	57
	FolC	.	.	.	.	.	.	2	.	.	.	2	.	3	.	.	7	14
	FolM	.	.	.	6	.	3	5	26	4	.	3	7	17	3	19	88	181
	FolF	.	1	.	2	.	4	2	3	18	.	1	1	4	.	3	53	92
	SepCM	.	.	.	.	.	.	1	1	.	.	.	.	5	.	.	3	10
	SepMM	.	.	.	1	.	.	2	3	1	.	15	.	3	.	5	11	41
	SepFR	.	.	.	.	.	.	.	.	1	.	2	1	.	.	.	11	15
	SepFM	.	.	.	.	.	1	1	6	4	.	13	1	2	.	6	56	90
	Cruis.	.	.	.	6	.	34	7	24	46	1	35	3	27	.	20	5	208
	Group Total	.	2	.	22	1	48	23	72	80	1	75	14	68	4	62	295	767
ICC at 2sec.	ClsCM	.	.	.	.	.	.	2	.	.	.	1	.	.	.	.	1	4
	ClsMM	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	2	3
	ClsFM	.	.	.	1	.	2	.	.	1	.	1	.	1	1	.	9	16
	FolC	.	.	.	.	.	.	.	.	1	.	1	.	1	.	.	3	6
	FolM	.	.	.	.	.	.	1	1	.	.	1	.	1	1	.	4	9
	FolF	.	.	.	3	.	3	1	.	24	1	1	1	5	.	7	51	97
	SepCR	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	SepCM	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1
	SepMM	.	.	.	.	.	.	.	.	3	.	4	1	3	.	1	5	17
	SepFR	.	.	.	.	.	.	.	.	.	.	.	1	1	.	.	4	6
	SepFM	.	.	.	.	.	.	.	2	5	.	2	1	2	.	3	34	49
	Cruis.	.	.	.	2	.	22	4	5	25	3	7	2	9	1	10	1	91
	Group Total	.	.	.	7	.	27	8	8	59	4	19	6	24	4	21	114	301

Table 3-20 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode and the Before/After Driving Sub-States - Freeways

Number of Lane Changes per Hundred Kilometers on Freeways
by Driving Sub-state before and after Lane Change
(ICC Combined)

Before Lane Change		Aafter Lane Change																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC
Manual	ClsCR	.	.	.	.01	.	.	.02	.01	.	.	.00	.	.	.	.	.02	.07
	ClsCM	.01	.06	.01	.05	.01	.06	.25	.08	.04	.03	.12	.03	.07	.	.03	.55	1.38
	ClsMR	.01	.00	.01	.01	.	.	.	.01	.	.	.00	.	.00	.	.	.05	.09
	ClsMM	.00	.08	.00	.11	.01	.04	.11	.17	.04	.	.04	.00	.13	.00	.01	.50	1.25
	ClsFR	.	.	.01	.	.00	.01	.00	.00	.00	.	.	.	.	.	.00	.03	.07
	ClsFM	.	.02	.	.08	.00	.05	.01	.03	.06	.	.00	.	.03	.01	.02	.30	.60
	FolC	.01	.11	.	.07	.01	.04	.51	.24	.11	.00	.30	.12	.26	.00	.05	.81	2.63
	FolM	.00	.08	.	.13	.	.05	.30	.52	.18	.01	.15	.01	.23	.00	.09	.92	2.68
	FolF	.	.01	.	.04	.00	.06	.13	.11	.52	.	.01	.01	.06	.00	.06	1.37	2.38
	SepCR	.	.	.	.	.	.	.	.	.	.	.	.	.01	.	.	.	.01
	SepCM	.	.	.	.00	.	.	.04	.02	.02	.	.01	.00	.04	.	.00	.02	.15
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.00	.05	.05
	SepMM	.	.01	.	.01	.	.00	.11	.11	.02	.01	.26	.00	.05	.01	.19	.18	.96
	SepFR	.	.	.	.	.	.	.	.	.	.00	.00	.	.01	.	.00	.09	.10
	SepFM	.	.	.	.02	.	.01	.08	.08	.04	.01	.16	.	.08	.01	.06	1.35	1.89
	Cruis.	.00	.02	.01	.19	.10	.92	.42	.41	.97	.04	.47	.13	.53	.05	.49	.06	4.82
	Group Total	.03	.39	.04	.72	.14	1.24	1.99	1.78	1.99	.11	1.52	.30	1.49	.09	1.02	6.29	19.13
CCC	ClsCR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	ClsCM	.	.	.	.00	.	.	.00	.04	.02	.	.03	.	.02	.	.01	.32	.44
	ClsMR	.	.	.	.	.	.	.	.	.01	.	.	.	.	.	.	.00	.02
	ClsMM	.	.03	.	.06	.01	.	.01	.08	.08	.	.00	.	.03	.	.	.31	.63
	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.06	.06
	ClsFM	.	.	.	.03	.	.06	.	.	.02	.	.	.	.01	.	.	.30	.42
	FolC	.	.	.	.	.	.	.	.02	.02	.	.03	.	.01	.	.	.33	.42
	FolM	.	.	.	.01	.02	.	.06	.06	.00	.	.05	.	.03	.	.01	.22	.46
	FolF	.	.	.	.	.	.16	.03	.05	.05	.	.01	.	.01	.	.01	.42	.74
	SepCM	.	.	.	.	.	.	.	.	.	.	.	.	.03	.	.	.	.03
	SepMM	.	.	.	.	.	.03	.	.	.01	.	.02	.	.01	.	.05	.08	.20
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.07	.07
	SepFM	.	.	.	.	.	.	.00	.01	.01	.	.03	.	.05	.00	.02	.89	1.01
	Cruis.	.	.	.	.03	.08	.32	.07	.15	.34	.01	.15	.01	.22	.02	1.03	.05	2.48
	Group Total	.	.03	.	.14	.11	.57	.18	.41	.57	.01	.32	.01	.42	.02	1.12	3.07	6.98
ICC Combined	ClsCM	.	.00	.	.00	.	.00	.03	.00	.00	.	.01	.	.00	.00	.01	.10	.16
	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	ClsMM	.	.02	.	.03	.	.	.02	.02	.00	.	.03	.00	.02	.01	.06	.18	.40
	ClsFR	.	.	.	.	.00	.01	.	.01	.	.	.	.	.00	.	.00	.03	.05
	ClsFM	.	.00	.	.02	.	.03	.01	.02	.02	.	.01	.	.03	.01	.01	.26	.42
	FolC	.	.	.	.00	.	.	.01	.01	.03	.01	.03	.01	.05	.	.01	.13	.27
	FolM	.	.01	.	.05	.	.04	.15	.19	.08	.	.10	.05	.12	.01	.06	.74	1.60
	FolF	.	.00	.	.08	.	.04	.01	.01	.28	.00	.02	.00	.03	.01	.08	.93	1.48
	SepCR	.	.	.	.	.	.	.	.	.	.	.00	.	.	.	.	.	.00
	SepCM	.	.	.	.01	.	.	.01	.01	.04	.	.01	.	.04	.	.	.02	.14
	SepMR	.	.	.	.	.	.	.	.	.	.	.00	.	.00	.00	.	.00	.01
	SepMM	.	.00	.	.00	.	.00	.01	.02	.02	.00	.11	.00	.04	.	.04	.10	.34
	SepFR	.	.	.	.	.	.	.	.	.01	.	.00	.01	.00	.00	.	.07	.09
	SepFM	.	.	.	.	.	.00	.03	.04	.04	.	.07	.00	.02	.	.05	.80	1.05
	Cruis.	.	.03	.	.04	.01	.47	.14	.17	.49	.01	.30	.04	.28	.02	.19	.05	2.24
	Group Total	.	.06	.	.22	.01	.59	.41	.50	1.01	.03	.69	.11	.62	.05	.51	3.43	8.27

Table 3-21 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode, ICC Headway Setting and the Before/After Driving Sub-States – Freeways

Number of Lane Changes per Hundred Kilometers on Freeways
by Driving Sub-state before and after Lane Change

Before Lane Change		After Lane Change																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate	Rate
Manual	ClsCR	.	.	.	.01	.	.	.02	.01	.	.	.00	.	.	.	.	.02	.07
	ClsCM	.01	.06	.01	.05	.01	.06	.25	.08	.04	.03	.12	.03	.07	.	.03	.55	1.38
	ClsMR	.01	.00	.01	.01	.	.	.	.01	.	.	.00	.	.00	.	.	.05	.09
	ClsMM	.00	.08	.00	.11	.01	.04	.11	.17	.04	.	.04	.00	.13	.00	.01	.50	1.25
	ClsFR	.	.	.01	.	.00	.01	.00	.00	.00	.	.	.	.	.	.00	.03	.07
	ClsFM	.	.02	.	.08	.00	.05	.01	.03	.06	.	.00	.	.03	.01	.02	.30	.60
	FolC	.01	.11	.	.07	.01	.04	.51	.24	.11	.00	.30	.12	.26	.00	.05	.81	2.63
	FolM	.00	.08	.	.13	.	.05	.30	.52	.18	.01	.15	.01	.23	.00	.09	.92	2.68
	FolF	.	.01	.	.04	.00	.06	.13	.11	.52	.	.01	.01	.06	.00	.06	1.37	2.38
	SepCR	.	.	.	.	.	.	.	.	.	.	.	.	.01	.	.	.	.01
	SepCM	.	.	.	.00	.	.	.04	.02	.02	.	.01	.00	.04	.	.00	.02	.15
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.00	.05	.05
	SepMM	.	.01	.	.01	.	.00	.11	.11	.02	.01	.26	.00	.05	.01	.19	.18	.96
	SepFR	.	.	.	.	.	.	.	.	.	.00	.00	.	.01	.	.00	.09	.10
	SepFM	.	.	.	.02	.	.01	.08	.08	.04	.01	.16	.	.08	.01	.06	1.35	1.89
	Cruis.	.00	.02	.01	.19	.10	.92	.42	.41	.97	.04	.47	.13	.53	.05	.49	.06	4.82
	Group Total	.03	.39	.04	.72	.14	1.24	1.99	1.78	1.99	.11	1.52	.30	1.49	.09	1.02	6.29	19.13
CCC	ClsCR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	ClsCM	.	.	.	.00	.	.	.00	.04	.02	.	.03	.	.02	.	.01	.32	.44
	ClsMR	.	.	.	.	.	.	.	.	.01	.	.	.	.	.	.	.00	.02
	ClsMM	.	.03	.	.06	.01	.	.01	.08	.08	.	.00	.	.03	.	.	.31	.63
	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.06	.06
	ClsFM	.	.	.	.03	.	.06	.	.	.02	.	.	.	.01	.	.	.30	.42
	FolC	.	.	.	.	.	.	.	.02	.02	.	.03	.	.01	.	.	.33	.42
	FolM	.	.	.	.01	.02	.	.06	.06	.00	.	.05	.	.03	.	.01	.22	.46
	FolF	.	.	.	.	.	.16	.03	.05	.05	.	.01	.	.01	.	.01	.42	.74
	SepCM	.	.	.	.	.	.	.	.	.	.	.	.	.03	.	.	.	.03
	SepMM	.	.	.	.	.	.03	.	.	.01	.	.02	.	.01	.	.05	.08	.20
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.07	.07
	SepFM	.	.	.	.	.	.	.00	.01	.01	.	.03	.	.05	.00	.02	.89	1.01
	Cruis.	.	.	.	.03	.08	.32	.07	.15	.34	.01	.15	.01	.22	.02	1.03	.05	2.48
	Group Total	.	.03	.	.14	.11	.57	.18	.41	.57	.01	.32	.01	.42	.02	1.12	3.07	6.98
ICC at 1sec.	ClsCM	.	.00	.	.01	.	.01	.01	.00	.00	.	.00	.	.00	.00	.02	.09	.15
	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.02	.02
	ClsMM	.	.05	.	.01	.	.	.05	.05	.01	.	.02	.	.05	.	.08	.19	.50
	ClsFR	.	.	.	.	.	.00	.	.02	.	.	.	.	.00	.	.	.06	.09
	ClsFM	.	.01	.	.02	.	.03	.01	.04	.01	.	.00	.	.01	.	.00	.20	.33
	FolC	.	.	.	.01	.	.	.01	.02	.07	.02	.05	.02	.10	.	.03	.16	.49
	FolM	.	.03	.	.01	.	.08	.17	.34	.20	.	.24	.05	.15	.01	.06	.96	2.31
	FolF	.	.	.	.02	.	.00	.00	.01	.21	.	.00	.	.03	.02	.06	.60	.95
	SepCM	.	.	.	.02	.	.	.04	.01	.12	.	.03	.	.02	.	.	.02	.25
	SepMR	.	.	.	.	.	.	.	.	.	.	.00	.	.00	.00	.	.01	.02
	SepMM	.	.00	.	.	.	.00	.01	.02	.01	.01	.15	.	.	.	.01	.02	.23
	SepFR	.	.	.	.	.	.	.	.	.01	.	.	.	.	.00	.	.07	.08
	SepFM	.	.	.	.	.	.01	.08	.01	.00	.	.11	.	.02	.	.06	.42	.70
	Cruis.	.	.09	.	.02	.04	.51	.10	.14	.44	.	.23	.02	.18	.04	.17	.02	2.00
	Group Total	.	.18	.	.11	.04	.65	.47	.66	1.10	.03	.84	.09	.56	.07	.48	2.84	8.12
ICC at 1.4sec	ClsCM	.	.00	.	.01	.	.	.02	.	.00	.	.	.	.	.	.00	.17	.21
	ClsMM	.	.	.	.05	.	.	.	.01	.	.	.07	.01	.01	.03	.09	.29	.57
	ClsFR	.	.	.	.	.00	.02	.	.	.	.	.	.	.	.	.00	.04	.06
	ClsFM	.	.	.	.01	.	.04	.00	.03	.04	.	.02	.	.02	.	.02	.32	.50
	FolC	.	.	.	.	.	.	.01	.	.	.	.01	.	.01	.	.	.18	.21
	FolM	.	.	.	.12	.	.03	.07	.20	.02	.	.03	.08	.14	.01	.11	1.00	1.82
	FolF	.	.00	.	.02	.	.02	.01	.02	.10	.	.05	.00	.02	.	.03	.53	.81
	SepCM	.	.	.	.	.	.	.01	.01	.	.	.	.	.05	.	.	.02	.09
	SepMM	.	.	.	.01	.	.	.01	.03	.01	.	.09	.	.01	.	.08	.14	.36
	SepFR	.	.	.	.	.	.	.	.	.01	.	.01	.00	.	.	.	.09	.12
	SepFM	.	.	.	.	.	.00	.00	.09	.03	.	.07	.01	.01	.	.06	.45	.72
	Cruis.	.	.	.	.05	.	.25	.09	.24	.43	.01	.46	.03	.20	.	.19	.12	2.07
	Group Total	.	.01	.	.27	.00	.37	.22	.64	.65	.01	.81	.13	.46	.04	.59	3.35	7.53
ICC at 2sec.	ClsCM	.	.	.	.	.	.	.08	.	.	.	.01	.	.	.	.	.01	.10
	ClsMM	.	.	.	.01	.	.	.	.	.	.	.	.	.	.	.	.03	.03
	ClsFM	.	.	.	.03	.	.02	.	.	.01	.	.01	.	.07	.02	.	.25	.42
	FolC	.	.	.	.	.	.	.	.	.01	.	.01	.	.03	.	.	.03	.08
	FolM	.	.	.	.	.	.	.23	.01	.	.	.01	.	.04	.01	.	.11	.41
	FolF	.	.	.	.24	.	.09	.01	.	.61	.01	.00	.01	.05	.	.16	1.89	3.08
	SepCR	.	.	.	.	.	.	.	.	.	.	.01	.	.	.	.	.	.01
	SepCM	.	.	.	.	.	.	.	.	.	.	.	.	.07	.	.	.	.07
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.00	.	.	.00
	SepMM	.	.	.	.	.	.	.	.	.05	.	.11	.01	.13	.	.01	.15	.46
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.01	.01	.	.	.05	.07
	SepFM	.	.	.	.	.	.	.	.02	.11	.	.02	.01	.02	.	.04	1.75	1.96
	Cruis.	.	.	.	.03	.	.74	.28	.09	.63	.03	.16	.08	.52	.01	.23	.00	2.79
	Group Total	.	.	.	.30	.	.85	.60	.12	1.42	.04	.35	.11	.93	.04	.45	4.27	9.49

The number of lane changes from one sub-state to another sub-state indicates the degree to which the data including the rate data are reliable. For example the numbers in many of the cells in the tables, particularly for CCC and the individual ICC headway settings are either zero (empty) or small. When comparing cells or groups of cells, a value of 30 or greater was considered acceptable for comparison.

The pattern of lane changes overall was the same for all three modes. The dominant before sub-state was cruise: 23 percent for manual, 30 percent for CCC and 25 percent for ICC. The dominant after sub-state was also cruise: 32 percent for manual, 43 percent for CCC and 38 percent of ICC. Furthermore, as noted above, a relatively large number *cruising-to-cruising* lane changes were essentially excluded from the transition and lane change analysis. The top two lane change maneuvers were the same for each mode: *cruising-to-closing-far-moderately* and *cruising-to-following-far*. The proportion of total lane changes for these two top maneuvers were all about the same: 5-6 percent.

There were very few lane changes to or from the *closing-close-rapidly, closing-middle-rapidly and closing-far-rapidly* sub-states. However the data tends to indicate that lane changes to the combined sub-states of *closing-close-rapidly, closing-middle-rapidly* and *closing-far-rapidly* occurred least often in terms of frequency for ICC (0.3 percent), followed by CCC (1.0 percent), and manual (1.3 percent). Furthermore, lane changes from the *closing-close-rapidly* and *closing-middle-rapidly* sub-states occurred less often in terms of frequency and rates for ICC compared to both manual and CCC. These results are considered safety beneficial for ICC since lane changes to or from, particularly, *closing-close* situations would be considered a safety-critical maneuver. Lane changes from the *closing-far-rapidly* sub-state occurred more often in terms of frequency but less often in terms of rates for ICC compared to both manual and CCC. The frequency result is not considered a safety concern for ICC, however, since *closing-far* sub-states are the least safety-critical of the *closing* sub-states.

When combined, there were a substantial number of lane changes that ended in one of the close sub-states. The highest occurrence of these lane changes were for manual (21 percent), followed by CCC (12 percent), and ICC (14 percent). Since any close sub-state is considered more safety-critical, this result indicates a safety benefit for ICC relative to manual.

There were substantially more lane changes to or from the *closing-close-moderately, closing-middle-moderately and closing-far-moderately* sub-states. Lane changes from the *closing-close-moderately* and *closing-middle-moderately* sub-states were less for ICC compared to manual in terms of the frequency and rates. Lane changes from the *closing-far-moderately* sub-state were more for ICC compared to manual in terms of the frequency and but less in terms of rates. The *closing-far* sub-state is the least safety-critical *closing* sub-state. There were less differences between ICC and CCC in the rates and frequency of lane changes from these three sub-states.

These results provide interesting insight into lane change behavior of drivers and the influence of the three control modes on that behavior. One perspective on lane changes is that drivers tend to make lane changes either voluntarily in response to their own needs or involuntarily in response to conditions imposed by other drivers (traffic). In the case of evaluating ICC, it is of interest to determine if the ICC system reduces the rate of involuntary lane changes that are in response to slower preceding vehicles. An indicator of such involuntary lane changes would be lane changes from the closing state, in general, and, more specifically, the *closing-close* sub-states. Because of the velocity and headway controlling features of ICC, it can be hypothesized that it would reduce such involuntary lane changes, particularly in contrast to CCC which has a fixed velocity function. A reduction in these types of lane changes would be viewed as safety beneficial since they are made in safety-critical situations of *closing-close* to another vehicle and the driver has little discretion over the timing of the lane change. The results, indeed, support this hypothesis. Lane changes from *closing-close* situations to all other sub-states represent only 2 percent of all ICC lane changes whereas they represent about 7 percent of lane changes for CCC and about 8 percent for manual. Figure 3-37 summarizes the results by cruise control mode in terms of the number of lane changes per hundred kilometers from each of the six closing sub-states. The rates are lower for ICC compared to both CCC and manual. These results are further evidence of the potential safety benefits of ICC in that it reduces the need for drivers to make safety-critical lane changes in response to slower traffic.

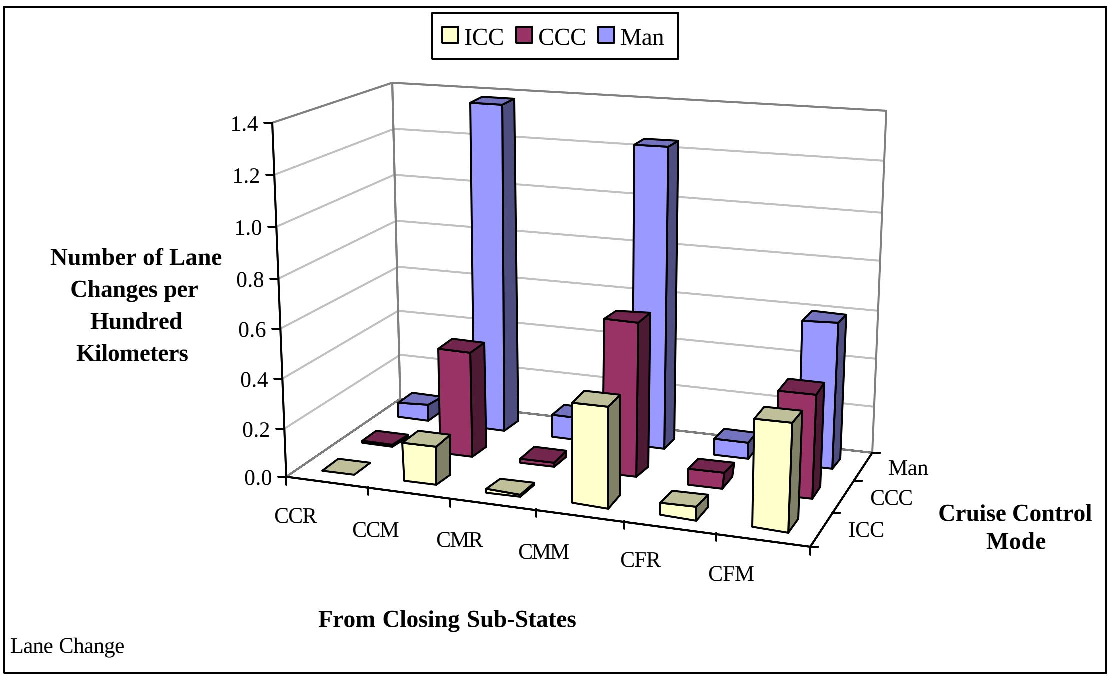

Figure 3-37 Number of Lane Changes per Hundred Kilometers From Closing Sub-States as a Function of Cruise Control Mode - Freeways

There were a substantial number of lane changes from the *following-close, following-middle*, and *following-far* sub-states for each of the modes for comparison. Lane changes from the *following-close* sub-state were substantially less for ICC compared to manual and CCC in terms of the frequency and rates. Lane changes from the *following-middle* and *following-far* sub-states were substantially greater for ICC compared to manual and CCC in terms of the frequency. In terms of rates, ICC was substantially less compared to manual but substantially greater compared to CCC. Again, these results indicate a safety benefit for ICC since the *following-close* sub-state is the most safety-critical of the following sub-states.

Summary: The number and pattern of lane changes indicate a strong safety benefit for ICC compared to both manual and CCC. There was, generally, a significantly lower rate of lane changes for ICC compared to manual. Furthermore, when they did occur, they were much less likely to start or end in a close sub-state, compared to both manual and CCC.

3.7.8 Lane Changes on Arterials

In this section the resulting lane change data on arterials are represented in terms of counts, frequency and rates as a function of cruise control mode, ICC headway setting, driving states and sub-states. The mean number of lane changes per hundred kilometers is shown in Figure 3-38 as a function of cruise control mode and ICC headway setting. It can be seen that there were significantly fewer lane changes with ICC and CCC when compared to the number of lane changes made in manual mode. The number of lane changes per hundred kilometers was reduced from approximately 17 for manual to 10 for CCC and 9 for ICC. There were substantially fewer lane changes with a headway setting of 2.0 seconds (6 lane changes per hundred kilometers) compared to the other two headway settings (approximately 11 lane changes per hundred kilometers). CCC and ICC overall were not significantly different.

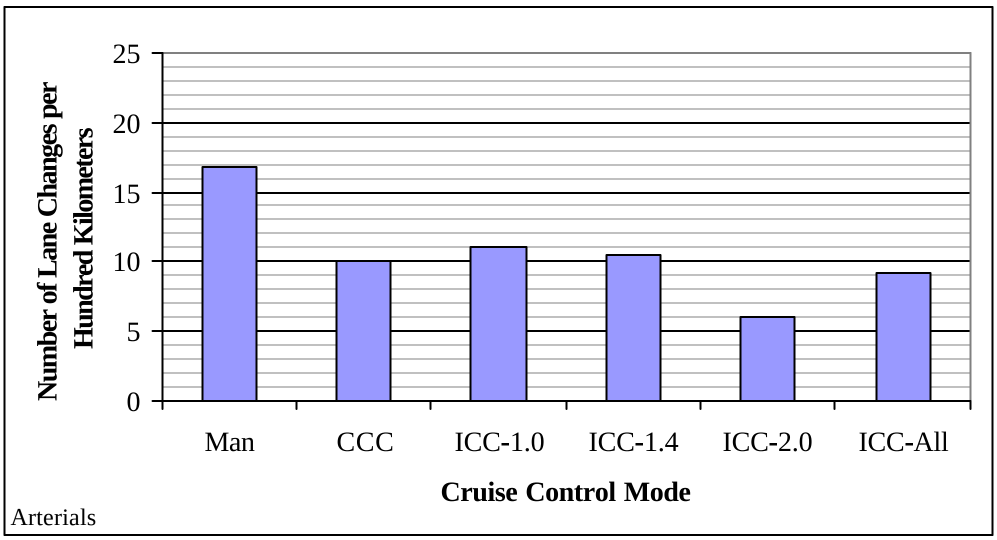

Figure 3-38 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode and ICC Headway Setting - Arterials

Table 3-22 shows the number of lane changes, and the number of lane changes per hundred kilometers as a function of cruise control mode and the before/after driving states. Table 3-23 shows similar data as a function of ICC headway settings. The main results for arterials were identical to those for freeways and are repeated next. There were substantially fewer lane changes made from the *closing* state with ICC compared to both manual and CCC. There were also substantially fewer lane changes made to the *closing* state with ICC compared to both manual and CCC. Relative to ICC headway setting, the fewest number of lane changes from the *closing* state were made with a headway setting of 2.0 seconds followed by a headway setting of 1.0 second. The fewest number of lane changes to the *closing* state were also made with a headway setting of 2.0 seconds followed by a headway setting of 1.0 second.

Table 3-22 Number of Lane Changes per Hundred Kilometers as a Function Of Cruise Control Mode - Arterials

Number of Lane Changes per Hundred Kilometers on Arterials
by Driving State before and after Lane Change
(ICC Combined)

Before Lane Change		After Lane Change: Closing No. of LC	Closing Rate of LC	Following No. of LC	Following Rate of LC	Separating No. of LC	Separating Rate of LC	Cruising No. of LC	Cruising Rate of LC	Total No. of LC	Total Rate of LC
Manual	Closing	120	.41	122	.43	29	.10	668	2.15	939	3.09
	Following	98	.31	481	1.72	117	.41	1000	3.34	1696	5.79
	Separating	12	.05	67	.26	67	.26	460	1.66	606	2.23
	Cruising	553	2.37	640	2.38	189	.70	80	.28	1462	5.73
	Group Total	783	3.14	1310	4.79	402	1.47	2208	7.44	4703	16.85
CCC	Closing	3	.17	2	.45	.	.	3	.19	8	.81
	Following	2	1.93	6	.30	.	.	6	1.82	14	4.05
	Separating	.	.	.	.	1	.12	8	.97	9	1.08
	Cruising	6	1.99	6	2.10	2	.06	2	.04	16	4.19
	Group Total	11	4.10	14	2.85	3	.18	19	3.01	47	10.13
ICC Combined	Closing	8	.09	2	.01	.	.	17	.52	27	.62
	Following	3	.08	17	1.57	8	.11	49	1.27	77	3.03
	Separating	.	.	1	.01	3	.06	39	1.82	43	1.89
	Cruising	31	.64	21	1.45	12	.40	.	.	64	2.49
	Group Total	42	.81	41	3.04	23	.57	105	3.62	211	8.03

Table 3-23 Number Of Lane Changes Per Hundred Kilometers as a Function Of Cruise Control Mode and ICC Headway Setting – Arterials

Number of Lane Changes per Hundred Kilometers on Arterials by Driving State before and after Lane Change

Before Lane Change		After Lane Change								Total	
		Closing		Following		Separating		Cruising		No. of LC	Rate of LC
		No. of LC	Rate of LC	No. of LC	Rate of LC	No. of LC	Rate of LC	No. of LC	Rate of LC		
Manual	Closing	120	.41	122	.43	29	.10	668	2.15	939	3.09
	Following	98	.31	481	1.72	117	.41	1000	3.34	1696	5.79
	Separating	12	.05	67	.26	67	.26	460	1.66	606	2.23
	Cruising	553	2.37	640	2.38	189	.70	80	.28	1462	5.73
	Group Total	783	3.14	1310	4.79	402	1.47	2208	7.44	4703	16.85
CCC	Closing	3	.17	2	.45	.	.	3	.19	8	.81
	Following	2	1.93	6	.30	.	.	6	1.82	14	4.05
	Separating	.	.	.	.	1	.12	8	.97	9	1.08
	Cruising	6	1.99	6	2.10	2	.06	2	.04	16	4.19
	Group Total	11	4.10	14	2.85	3	.18	19	3.01	47	10.13
ICC at 1sec.	Closing	5	.18	1	.04	.	.	6	.30	12	.52
	Following	2	.16	3	.76	4	.21	16	1.61	25	2.74
	Separating	.	.	1	.02	.	.	8	2.61	9	2.63
	Cruising	10	1.24	8	3.59	4	.41	.	.	22	5.24
	Group Total	17	1.58	13	4.41	8	.62	30	4.52	68	11.13
ICC at 1.4sec	Closing	1	.03	1	.00	.	.	9	1.02	11	1.05
	Following	.	.	10	3.26	3	.09	19	1.52	32	4.87
	Separating	.	.	.	.	.	.	14	.89	14	.89
	Cruising	12	2.26	5	.73	6	.60	.	.	23	3.59
	Group Total	13	2.29	16	4.00	9	.68	42	3.44	80	10.41
ICC at 2sec.	Closing	2	.06	.	.	.	.	2	.09	4	.15
	Following	1	.09	4	.15	1	.04	14	.81	20	1.09
	Separating	.	.	.	.	3	.19	17	3.34	20	3.53
	Cruising	9	.63	8	.55	2	.14	.	.	19	1.31
	Group Total	12	.78	12	.70	6	.38	33	4.23	63	6.08

Tables 3-24 through 3-26 show, respectively, the number of lane changes as a function of cruise control mode, ICC headway setting, and the before/after driving sub-states (16x16 matrices); the number of lane changes per hundred kilometers as a function of cruise control mode and the before/after driving sub-states; and the number of lane changes per hundred kilometers as a function of ICC headway setting and the before/after driving sub-states.

Table 3-24 Number of Lane Changes as a Function of Cruise Control Mode, ICC Headway Setting, and the Before/After Driving Sub-States – Arterials

Number of Lane Changes on Arterials
by Driving Sub-state before and after Lane Change

Before Lane Change		After Lane Change															Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
Manual	ClsCR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	3
	ClsCM	.	2	.	.	1	5	23	9	10	.	.	4	.	1	129	184
	ClsMR	.	.	2	3	1	.	.	1	1	.	.	.	.	.	41	49
	ClsMM	.	10	1	17	.	12	7	31	13	2	.	4	.	9	299	405
	ClsFR	.	.	5	.	.	5	.	2	.	.	.	.	.	1	38	51
	ClsFM	.	4	3	19	4	26	1	6	18	.	.	1	.	7	158	247
	FolC	.	4	.	5	.	5	21	25	16	8	.	10	.	7	140	241
	FolM	.	3	2	25	.	19	30	117	50	3	.	45	.	17	320	631
	FolF	.	4	.	12	.	19	10	34	178	1	.	1	.	25	540	824
	SepCM	.	.	.	.	.	.	.	1	.	.	.	4	.	.	.	5
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
	SepMM	.	1	.	1	.	4	5	11	5	5	.	6	.	17	29	84
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	8	8
	SepFM	.	2	.	2	.	2	5	9	31	5	.	7	.	23	422	508
	Cruis.	.	5	7	32	54	455	58	88	494	17	7	87	2	76	80	1462
	Group Total	.	35	20	116	60	552	160	334	816	41	7	169	2	183	2208	4703
CCC	ClsMM	.	.	.	.	.	.	.	1	.	.	.	.	.	.	1	2
	ClsFM	.	.	.	.	.	3	1	.	.	.	.	.	.	.	2	6
	FolC	.	.	.	.	.	1	.	.	.	.	.	.	.	.	1	2
	FolM	.	.	.	.	.	.	.	1	2	.	.	.	.	.	1	4
	FolF	.	.	.	.	.	1	.	.	3	.	.	.	.	.	4	8
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	3
	SepFM	.	.	.	.	.	.	.	.	.	.	.	1	.	.	4	5
	Cruis.	.	.	.	.	.	6	1	1	4	1	1	.	.	.	2	16
	Group Total	.	.	.	.	.	11	2	3	9	1	1	1	.	.	19	47
ICC at 1sec.	ClsCM	1	.	.	.	.	1	.	.	.	.	.	.	.	.	1	3
	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
	ClsMM	.	.	.	.	.	1	1	.	.	.	.	.	.	.	1	3
	ClsFR	.	.	1	.	.	.	.	.	.	.	.	.	.	.	2	3
	ClsFM	.	.	.	.	.	1	.	.	.	.	.	.	.	.	1	2
	FolC	.	.	.	.	.	.	.	.	.	1	.	1	.	.	1	3
	FolM	.	.	.	2	.	.	1	.	.	.	.	1	.	1	9	14
	FolF	.	.	.	.	.	.	.	1	1	.	.	.	.	.	6	8
	SepFM	.	.	.	.	.	.	.	.	1	.	.	.	.	.	8	9
	Cruis.	.	.	.	.	2	8	.	1	7	.	1	2	.	1	.	22
	Group Total	1	.	1	2	2	11	2	2	9	1	1	4	.	2	30	68
ICC at 1.4sec	ClsCM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	2
	ClsMM	.	.	.	1	.	.	.	1	.	.	.	.	.	.	5	7
	ClsFM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	2
	FolM	.	.	.	.	.	.	.	2	1	1	.	1	.	.	6	11
	FolF	.	.	.	.	.	.	.	.	7	.	.	.	1	.	13	21
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	3
	SepFM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	11	11
	Cruis.	.	.	.	1	2	9	.	.	5	1	.	3	1	1	.	23
	Group Total	.	.	.	2	2	9	.	3	13	2	.	4	2	1	42	80
ICC at 2sec.	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
	ClsMM	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
	ClsFM	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1	2
	FolM	.	.	.	.	.	.	.	2	.	.	.	.	.	.	2	4
	FolF	.	.	.	.	.	1	1	.	1	.	.	1	.	.	12	16
	SepMM	.	.	.	.	.	.	.	.	.	.	.	1	.	.	2	3
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
	SepFM	.	.	.	.	.	.	.	.	.	.	.	.	.	2	14	16
	Cruis.	.	.	1	1	.	7	.	.	8	.	.	2	.	.	.	19
	Group Total	.	.	1	1	1	9	1	2	9	.	.	4	.	2	33	63

It is to be noted that there are very few lane changes for CCC and the individual ICC headway settings. No cells, other than the sub-totals had more than 9 lane changes. Therefore, no further analysis was conducted at this level for CCC or for ICC at the individual headway settings.

The pattern of lane changes overall was the same for all three modes. The dominant before sub-state was *cruising*: 31 percent for manual, 34 percent for CCC and 29 percent for ICC. The dominant after sub-state was also *cruising*: 47 percent for manual, 40 percent for CCC and 41 percent of ICC.

In the manual mode, the main "before/after" lane changes were as follows: *following-far to cruising* (11.5 percent), *cruising to following-far* (10.5 percent), *cruising to closing-far-moderately* (9.7 percent), and *separating-far-moderately to cruising* (9.0 percent). Further, in the manual mode, the occurrence of the "before" *close* sub-states was 9.2 percent, "before" *closing-rapidly* sub-states was 2.2 percent, "after" *close* sub-states was 5.0 percent, and "after" *closing-rapidly* sub-state was 1.7 percent.

Table 3-25 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode, and the Before/After Driving Sub-States – Arterials

Number of Lane Changes per Hundred Kilometers on Arterials by Driving Sub-state before and after Lane Change (ICC Combined)

Before Lane Change		After Lane Change ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	Total
		Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC	Rate of LC
Manual	ClsCR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	ClsCM	.	.01	.	.	.00	.01	.08	.02	.04	.	.	.02	.	.00	.39	.57
	ClsMR	.	.	.00	.01	.00	.	.	.00	.00	.	.	.	.	.	.15	.17
	ClsMM	.	.04	.00	.05	.	.03	.02	.11	.04	.00	.	.01	.	.03	.89	1.23
	ClsFR	.	.	.01	.	.	.03	.	.00	.	.	.	.	.	.00	.11	.16
	ClsFM	.	.02	.01	.06	.01	.11	.00	.03	.08	.	.	.00	.	.03	.60	.95
	FolC	.	.01	.	.02	.	.01	.06	.11	.05	.02	.	.03	.	.03	.47	.81
	FolM	.	.01	.00	.07	.	.05	.08	.41	.15	.01	.	.12	.	.06	1.03	1.99
	FolF	.	.02	.	.08	.	.05	.03	.14	.69	.01	.	.00	.	.14	1.84	2.99
	SepCM	.	.	.	.	.	.	.	.00	.	.	.	.01	.	.	.	.01
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	SepMM	.	.00	.	.00	.	.02	.02	.03	.03	.02	.	.03	.	.06	.12	.33
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.04	.04
	SepFM	.	.00	.	.01	.	.01	.01	.04	.13	.03	.	.03	.	.08	1.50	1.84
	Cruis.	.	.03	.04	.10	.20	2.00	.18	.28	1.92	.06	.03	.33	.01	.27	.28	5.73
	Group Total	.	.15	.06	.39	.21	2.32	.48	1.19	3.12	.14	.03	.59	.01	.71	7.44	16.85
CCC	ClsMM	.	.	.	.	.	.	.	.36	.	.	.	.	.	.	.07	.43
	ClsFM	.	.	.	.	.	.17	.09	.	.	.	.	.	.	.	.12	.38
	FolC	.	.	.	.	.	.09	.	.	.	.	.	.	.	.	.04	.13
	FolM	.	.	.	.	.	.	.	.12	.08	.	.	.	.	.	.04	.24
	FolF	.	.	.	.	.	1.85	.	.	.10	.	.	.	.	.	1.74	3.68
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.14	.14
	SepFR	.	.	.	.	.		.	.	.	.	.	.	.	.	.74	.74
	SepFM	.	.	.	.	.	.	.	.	.	.	.	.12	.	.	.09	.21
	Cruis.	.	.	.	.	.	1.99	.04	.07	1.99	.04	.02	.	.	.	.04	4.19
	Group Total	.	.	.	.	.	4.10	.13	.56	2.17	.04	.02	.12	.	.	3.01	10.13
ICC Combined	ClsCM	.01	.	.	.	.	.01	.	.	.	.	.	.	.	.	.04	.06
	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.04	.04
	ClsMM	.	.	.	.01	.	.02	.01	.00	.	.	.	.	.	.	.33	.38
	ClsFR	.	.	.01	.	.	.	.	.	.	.	.	.	.	.	.04	.05
	ClsFM	.	.	.	.	.01	.02	.	.	.	.	.	.	.	.	.07	.09
	FolC	.	.	.	.	.	.	.	.	.	.01	.	.01	.	.	.01	.03
	FolM	.	.	.	.05	.	.	.01	.41	.04	.01	.	.04	.	.01	.27	.86
	FolF	.	.	.	.	.	.02	.02	.02	1.08	.	.	.01	.01	.	.98	2.14
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.01	.	.	.02	.04
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.25	.25
	SepFM	.	.	.	.	.	.	.	.	.01	.	.	.	.	.04	1.55	1.60
	Cruis.	.	.	.02	.06	.17	.40	.	.79	.65	.18	.02	.08	.02	.10	.	2.49
	Group Total	.01	.	.03	.12	.17	.48	.04	1.22	1.78	.20	.02	.17	.03	.15	3.62	8.03

Table 3-26 Number of Lane Changes per Hundred Kilometers as a Function of Cruise Control Mode, ICC Headway Setting, and the Before/After Driving Sub-States – Arterials

Number of Lane Changes per Hundred Kilometers on Arterials by Driving Sub-state before and after Lane Change

Before Lane Change		After Lane Change															Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC	Rate Of LC
Manual	ClsCR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	ClsCM	.	.01	.	.	.00	.01	.08	.02	.04	.	.	.02	.	.00	.39	.57
	ClsMR	.	.	.00	.01	.00	.	.	.00	.00	.	.	.	.	.	.15	.17
	ClsMM	.	.04	.00	.05	.	.03	.02	.11	.04	.00	.	.01	.	.03	.89	1.23
	ClsFR	.	.	.01	.	.	.03	.	.00	.	.	.	.	.	.00	.11	.16
	ClsFM	.	.02	.01	.06	.01	.11	.00	.03	.08	.	.	.00	.	.03	.60	.95
	FolC	.	.01	.	.02	.	.01	.06	.11	.05	.02	.	.03	.	.03	.47	.81
	FolM	.	.01	.00	.07	.	.05	.08	.41	.15	.01	.	.12	.	.06	1.03	1.99
	FolF	.	.02	.	.08	.	.05	.03	.14	.69	.01	.	.00	.	.14	1.84	2.99
	SepCM	.	.	.	.	.	.	.	.00	.	.	.	.01	.	.	.	.01
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	SepMM	.	.00	.	.00	.	.02	.02	.03	.03	.02	.	.03	.	.06	.12	.33
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.04	.04
	SepFM	.	.00	.	.01	.	.01	.01	.04	.13	.03	.	.03	.	.08	1.50	1.84
	Cruis.	.	.03	.04	.10	.20	2.00	.18	.28	1.92	.06	.03	.33	.01	.27	.28	5.73
	Group Total	.	.15	.06	.39	.21	2.32	.48	1.19	3.12	.14	.03	.59	.01	.71	7.44	16.85
CCC	ClsMM	.	.	.	.	.	.	.	.36	.	.	.	.	.	.	.07	.43
	ClsFM	.	.	.	.	.	.17	.09	.	.	.	.	.	.	.	.12	.38
	FolC	.	.	.	.	.	.09	.	.	.	.	.	.	.	.	.04	.13
	FolM	.	.	.	.	.	.	.	.12	.08	.	.	.	.	.	.04	.24
	FolF	.	.	.	.	.	1.85	.	.	.10	.	.	.	.	.	1.74	3.68
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.14	.14
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.74	.74
	SepFM	.	.	.	.	.	.	.	.	.	.	.	.12	.	.	.09	.21
	Cruis.	.	.	.	.	.	1.99	.04	.07	1.99	.04	.02	.	.	.	.04	4.19
	Group Total	.	.	.	.	.	4.10	.13	.56	2.17	.04	.02	.12	.	.	3.01	10.13
ICC at 1sec.	ClsCM	.02	.	.	.	.	.04	.	.	.	.	.	.	.	.	.05	.11
	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.06	.06
	ClsMM	.	.	.	.	.	.02	.04	.	.	.	.	.	.	.	.02	.08
	ClsFR	.	.	.04	.	.	.	.	.	.	.	.	.	.	.	.11	.16
	ClsFM	.	.	.	.	.	.05	.	.	.	.	.	.	.	.	.06	.11
	FolC	.	.	.	.	.	.	.	.	.	.02	.	.04	.	.	.04	.10
	FolM	.	.	.	.16	.	.	.02	.	.	.	.	.10	.	.04	.59	.92
	FolF	.	.	.	.	.	.	.	.05	.69	.	.	.	.	.	.98	1.72
	SepFM	.	.	.	.	.	.	.	.	.02	.	.	.	.	.	2.61	2.63
	Cruis.	.	.	.	.	.48	.76	.	2.49	1.09	.	.05	.07	.	.29	.	5.24
	Group Total	.02	.	.04	.16	.48	.88	.06	2.54	1.81	.02	.05	.21	.	.33	4.52	11.13
ICC at 1.4sec	ClsCM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.07	.07
	ClsMM	.	.	.	.03	.	.	.	.00	.	.	.	.	.	.	.83	.87
	ClsFM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.12	.12
	FolM	.	.	.	.	.	.	.	.99	.11	.03	.	.03	.	.	.16	1.32
	FolF	.	.	.	.	.	.	.	.	2.16	.	.	.	.03	.	1.36	3.56
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.12	.12
	SepFM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.77	.77
	Cruis.	.	.	.	.11	.03	2.12	.	.	.73	.46	.	.07	.06	.01	.	3.59
	Group Total	.	.	.	.14	.03	2.12	.	.99	3.01	.49	.	.10	.09	.01	3.44	10.41
ICC at 2sec.	ClsMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.07	.07
	ClsMM	.	.	.	.	.	.04	.	.	.	.	.	.	.	.	.	.04
	ClsFM	.	.	.	.	.02	.	.	.	.	.	.	.	.	.	.02	.04
	FolM	.	.	.	.	.	.	.	.08	.	.	.	.	.	.	.17	.25
	FolF	.	.	.	.	.	.09	.06	.	.02	.	.	.04	.	.	.63	.84
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.04	.	.	.09	.13
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.72	.72
	SepFM	.	.	.	.	.	.	.	.	.	.	.	.	.	.15	2.53	2.69
	Cruis.	.	.	.07	.04	.	.52	.	.	.55	.	.	.14	.	.	.	1.31
	Group Total	.	.	.07	.04	.02	.65	.06	.08	.57	.	.	.22	.	.15	4.23	6.08

Summary: The number of lane changes on arterials indicate a strong safety benefit for ICC compared to both manual and CCC. The overall pattern of the lane changes seemed to be the same in that the dominant "before" sub-state, and the dominant "after" sub-state" was cruising. The pattern of lane changes in terms of the other sub-states could not be discerned because of the paucity of data.

3.7.9 Cut-Ins on Freeways

In this section the resulting cut-in data on freeways are represented in terms of counts, frequency and rates as a function of cruise control mode, ICC headway setting, driving states and sub-states. Cut-ins occur at the discretion of the other driver and as such their occurrence represents more of an exposure to a particular type of traffic circumstance rather than the host drivers reaction to a traffic situation. Similar to lane changes, cut-ins are described and analyzed in this section in terms of their immediate "before" sub-state and their immediate "after sub-state. It was hypothesized that, with larger headways, there are more opportunities for cut-ins, and since, as will be seen in Section 3.8.1, ICC has longer headways, ICC would also have more cut-ins. This section also examines cut-ins as a function of ICC headway setting for similar reasons. Finally, the type of cut-in is examined, particularly safety-critical *close* cut-ins, and *closing-rapidly* cut-ins. Cut-ins are a different manifestation of lane changes and thus similarly increase turbulence in traffic flow. An ICC contribution to an increase in cut-ins would be an indication of a negative safety effect.

The mean number of cut-ins per hundred kilometers is shown in Figure 3-39 as a function of cruise control mode and ICC headway setting. The results, not surprisingly from a traffic symmetry point of view, are somewhat similar to the results for lane changes. The magnitudes are about the same and there were significantly fewer lane changes with ICC and CCC when compared to the number of cut-ins made in manual mode. The number of cut-ins per hundred kilometers was reduced from approximately 20 for manual to 12 for both ICC and CCC. The reduction in cut-ins associated with use of the ICC system indicates a general safety benefit for ICC relative to manual.

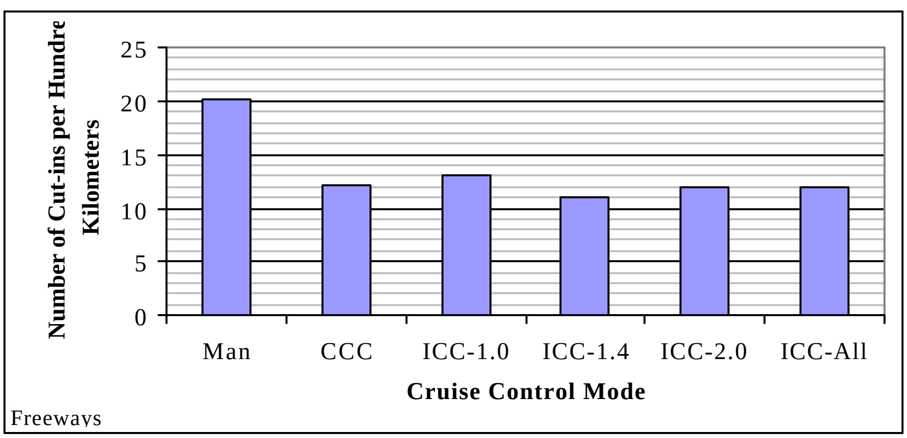

Figure 3-39 Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode and ICC Headway Setting – Freeways

There were only minor differences in cut-ins between the three ICC headway settings. Thus the hypothesis that longer headway settings lead to more cut-ins is not supported by these results.

If cut-ins increase the probability of crashes, then ICC reduces the probability of crashes attributable to cut-ins, relative to manual driving, and thus provides a safety benefit. A further examination of cut-in scenarios is given in Sections 3.9.2.1 and 3.9.2.2.

Table 3-27 shows the number of cut-ins, and the number of cut-ins per hundred kilometers as a function of cruise control mode and the before/after driving states. Table 3-28 shows similar data as a function of ICC headway settings. There were substantially fewer cut-ins made from the *closing* state with ICC compared to manual. ICC and CCC were about the same. There were also substantially fewer cut-ins made to the *closing* state with ICC compared to manual. and CCC. Again, ICC and CCC were about the same. Since any maneuver from or to a *closing* state is considered more safety-critical than maneuvers involving other states, this is considered an indication of a safety benefit for ICC relative to manual and CCC. Relative to ICC headway setting, the lowest rate of cut-ins from the *closing* state were made with a headway setting of 2.0 seconds. The cut-in rates from the *closing* state were nearly identical at 2.4 cut-ins per hundred kilometers for headway settings of 1.0 second and 1.4 seconds. The lowest rate of cut-ins to the *closing* state were also made with a headway setting of 2.0 seconds. Headway settings of 1.0 second resulted in the highest rate of cut-ins to the *closing* state. Thus, even though the longer 2.0 second headway setting had an overall cut-in rate about equal to the shorter settings, it had the lowest rate of cut-ins to and from the most safety-critical closing state.

Table 3-27 Number of Cut-Ins and the Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode - Freeways

Number of Cut-ins per Hundred Kilometers on Freeways by Driving State before and after Cut-in (ICC Combined)

Before Cut-in		After Cut-in								Total	
		Closing		Following		Separating		Cruising			
		No. of CI	Rate of CI	No. of CI	Rate of CI	No. of CI	Rate of CI	No. of CI	Rate of CI	No. of CI	Rate of CI
Manual	Closing	656	2.43	337	1.25	78	.28	123	.47	1194	4.43
	Following	332	1.28	908	3.59	305	1.42	50	.29	1595	6.58
	Separating	53	.22	263	1.05	315	1.81	41	.21	672	3.29
	Cruising	108	.49	440	1.85	583	3.42	40	.16	1171	5.92
	Group Total	1149	4.42	1948	7.74	1281	6.93	254	1.13	4632	20.22
CCC	Closing	114	1.35	29	.28	15	.15	21	.24	179	2.01
	Following	29	.48	69	.95	48	.51	6	.04	152	1.98
	Separating	11	.09	34	.35	120	1.48	11	.12	176	2.04
	Cruising	17	.19	106	1.59	326	4.05	10	.21	459	6.03
	Group Total	171	2.10	238	3.17	509	6.18	48	.60	966	12.05
ICC Combined	Closing	310	1.25	102	.39	60	.16	50	.21	522	2.01
	Following	204	.91	387	1.34	312	1.54	39	.17	942	3.97
	Separating	30	.09	103	.34	310	1.32	26	.09	469	1.84
	Cruising	57	.22	271	1.25	597	2.57	29	.11	954	4.15
	Group Total	601	2.48	863	3.32	1279	5.58	144	.58	2887	11.97

Table 3-28 Number of Cut-Ins and the Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode and Headway Setting- Freeways

Number of Cut-ins per Hundred Kilometers on Freeways by Driving State before and after Cut-in

Before Cut-in		After Cut-in: Closing No. of CI	Closing Rate of Cut-in	Following No. of CI	Following Rate of Cut-in	Separating No. of CI	Separating Rate of Cut-in	Cruising No. of CI	Cruising Rate of Cut-in	Total No. of CI	Total Rate of Cut-in
Manual	Closing	656	2.43	337	1.25	78	.28	123	.47	1194	4.43
	Following	332	1.28	908	3.59	305	1.42	50	.29	1595	6.58
	Separating	53	.22	263	1.05	315	1.81	41	.21	672	3.29
	Cruising	108	.49	440	1.85	583	3.42	40	.16	1171	5.92
	Group Total	1149	4.42	1948	7.74	1281	6.93	254	1.13	4632	20.22
CCC	Closing	114	1.35	29	.28	15	.15	21	.24	179	2.01
	Following	29	.48	69	.95	48	.51	6	.04	152	1.98
	Separating	11	.09	34	.35	120	1.48	11	.12	176	2.04
	Cruising	17	.19	106	1.59	326	4.05	10	.21	459	6.03
	Group Total	171	2.10	238	3.17	509	6.18	48	.60	966	12.05
ICC at 1sec.	Closing	184	1.71	48	.32	26	.19	32	.21	290	2.43
	Following	105	1.28	165	1.43	87	1.72	12	.07	369	4.50
	Separating	15	.18	36	.22	90	1.48	6	.10	147	1.99
	Cruising	24	.26	124	1.34	156	2.60	7	.04	311	4.23
	Group Total	328	3.42	373	3.32	359	5.99	57	.42	1117	13.15
ICC at 1.4sec	Closing	101	1.45	44	.56	28	.21	10	.20	183	2.41
	Following	75	.58	153	1.28	121	1.15	18	.19	367	3.20
	Separating	12	.07	41	.30	136	1.02	15	.11	204	1.50
	Cruising	20	.24	96	.84	310	2.60	14	.20	440	3.88
	Group Total	208	2.34	334	2.98	595	4.97	57	.70	1194	10.99
ICC at 2sec.	Closing	25	.42	10	.23	6	.05	8	.23	49	.92
	Following	24	.92	69	1.33	104	1.85	9	.27	206	4.37
	Separating	3	.02	26	.52	84	1.55	5	.04	118	2.13
	Cruising	13	.16	51	1.72	131	2.48	8	.09	203	4.45
	Group Total	65	1.52	156	3.80	325	5.92	30	.62	576	11.87

Tables 3-29 through 3-32 show, respectively, the number of cut-ins as a function of cruise control mode and the before/after driving sub-states (16x16 matrices); the number of cut-ins as a function of cruise control mode, ICC headway setting and the before/after driving sub-states; the number of cut-ins per hundred kilometers as a function of cruise control mode and the before/after driving sub-states; and the number of cut-ins per hundred kilometers as a function of cruise control mode, ICC headway setting and the before/after driving sub-states.

Table 3-29 Number of Cut-Ins as a Function Of Cruise Control Mode and the Before/After Driving Sub-States - Freeways

Number of Cut-ins on Freeways
by Driving Sub-state before and after Cut-in

Before Cut-in		After Cut-in																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
Manual	ClsCR	.	5	.	.	.	.	5	.	1	.	1	.	.	.	.	.	12
	ClsCM	.	18	.	1	.	1	58	6	1	.	15	.	1	.	2	6	109
	ClsMR	8	6	7	20	.	.	3	2	.	.	1	.	1	.	.	7	55
	ClsMM	3	76	5	102	.	6	66	74	2	.	17	.	4	.	4	42	401
	ClsFR	.	3	34	13	7	32	.	4	2	.	.	.	.	.	.	9	104
	ClsFM	2	13	11	124	11	148	26	49	38	.	9	.	15	.	8	59	513
	FolC	.	13	.	3	.	.	49	14	1	.	20	.	7	.	.	4	111
	FolM	7	85	3	54	1	3	410	68	4	1	94	1	34	1	9	16	791
	FolF	2	22	4	91	3	41	123	220	19	.	68	2	56	1	11	30	693
	SepCM	.	.	.	.	.	.	12	.	.	.	5	.	7	.	.	.	24
	SepMR	.	.	.	.	.	.	2	.	1	.	1	2	2	1	.	.	9
	SepMM	1	14	.	2	.	.	92	20	1	.	95	.	16	.	5	5	251
	SepFR	.	1	.	1	.	.	.	.	1	.	2	5	3	.	1	1	15
	SepFM	.	5	.	25	.	4	43	76	15	1	65	3	90	.	11	35	373
	Cruis.	2	16	6	84	.	.	98	162	180	7	140	29	241	15	151	40	1171
	Group Total	25	277	70	520	22	235	987	695	266	9	533	42	477	18	202	254	4632
CCC	ClsCR	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	1
	ClsCM	.	1	.	.	.	.	2	.	.	.	3	.	.	.	.	2	8
	ClsMR	1	.	2	5	.	.	.	.	.	.	.	.	.	.	.	.	8
	ClsMM	.	11	1	25	.	1	4	4	2	.	2	.	2	.	.	14	66
	ClsFR	.	.	3	2	1	3	.	.	.	.	.	.	.	.	.	1	10
	ClsFM	.	2	1	24	4	27	.	9	7	.	2	.	5	.	1	4	86
	FolC	1	.	.	.	.	.	1	.	.	.	1	.	.	.	.	1	4
	FolM	1	5	.	4	.	.	15	5	2	2	14	.	3	.	.	1	52
	FolF	.	.	2	10	.	6	18	26	2	.	10	.	12	.	6	4	96
	SepCM	.	.	.	.	.	.	2	.	.	.	.	.	8	.	.	.	10
	SepMM	.	2	.	2	.	1	7	2	.	1	25	.	1	.	7	.	48
	SepFR	.	.	.	.	.	.	.	.	.	1	1	4	1	.	.	2	9
	SepFM	.	1	1	2	.	2	3	14	6	.	23	6	38	.	4	9	109
	Cruis.	.	1	1	15	.	.	21	33	52	3	72	23	127	11	90	10	459
	Group Total	3	23	11	89	5	40	73	93	72	7	153	33	197	11	108	48	966
ICC Combined	ClsCR	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
	ClsCM	.	6	.	.	.	.	10	.	.	.	1	.	.	.	.	3	20
	ClsMR	2	.	.	4	.	.	.	.	.	.	.	.	.	.	.	1	7
	ClsMM	.	26	3	27	.	3	13	12	2	2	10	.	9	.	1	13	121
	ClsFR	.	1	11	4	4	15	2	1	1	.	1	.	.	.	.	2	42
	ClsFM	.	4	6	84	4	106	10	31	19	.	12	2	14	.	8	31	331
	FolC	.	.	.	.	.	.	7	2	.	.	8	.	.	.	.	.	17
	FolM	.	66	.	31	.	1	137	26	4	1	74	2	47	.	5	14	408
	FolF	.	12	.	73	1	20	57	133	21	1	76	5	80	1	12	25	517
	SepCR	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	SepCM	.	.	.	.	.	.	4	.	.	.	3	.	4	.	.	.	11
	SepMR	.	.	.	.	.	.	.	.	.	.	1	.	.	2	1	.	4
	SepMM	.	3	.	3	.	1	26	12	1	1	61	1	21	.	9	2	141
	SepFR	.	.	.	.	.	.	.	2	.	.	6	7	11	1	1	4	32
	SepFM	1	5	.	13	1	3	8	36	14	1	68	8	90	2	10	20	280
	Cruis.	.	8	1	48	.	.	35	92	144	10	131	52	229	19	156	29	954
	Group Total	3	131	21	287	10	149	310	347	206	16	453	77	505	25	203	144	2887

Table 3-30 Number of Cut-Ins as a Function of Cruise Control Mode, ICC Headway Setting and the Before/After Driving Sub-States – Freeways

Number of Cut-ins on Freeways
by Driving Sub-state before and after Cut-in

Before Cut-in		After Cut-in																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
Manual	ClsCR	.	5	.	.	.	.	5	.	1	.	1	.	.	.	.	.	12
	ClsCM	.	18	.	1	.	1	58	6	1	.	15	.	1	.	2	6	109
	ClsMR	8	6	7	20	.	.	3	2	.	.	1	.	1	.	.	7	55
	ClsMM	3	76	5	102	.	6	66	74	2	.	17	.	4	.	4	42	401
	ClsFR	.	3	34	13	7	32	.	4	2	.	.	.	.	.	.	9	104
	ClsFM	2	13	11	124	11	148	26	49	38	.	9	.	15	.	8	59	513
	FolC	.	13	.	3	.	.	49	14	1	.	20	.	7	.	.	4	111
	FolM	7	85	3	54	1	3	410	68	4	1	94	1	34	1	9	16	791
	FolF	2	22	4	91	3	41	123	220	19	.	68	2	56	1	11	30	693
	SepCM	.	.	.	.	.	.	12	.	.	.	5	.	7	.	.	.	24
	SepMR	.	.	.	.	.	.	2	.	1	.	1	2	2	1	.	.	9
	SepMM	1	14	.	2	.	.	92	20	1	.	95	.	16	.	5	5	251
	SepFR	.	1	.	1	.	.	.	.	1	.	2	5	3	.	1	1	15
	SepFM	.	5	.	25	.	4	43	76	15	1	65	3	90	.	11	35	373
	Cruis.	2	16	6	84	.	.	98	162	180	7	140	29	241	15	151	40	1171
	Group Total	25	277	70	520	22	235	987	695	266	9	533	42	477	18	202	254	4632
CCC	ClsCR	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	1
	ClsCM	.	1	.	.	.	.	2	.	.	.	3	.	.	.	.	2	8
	ClsMR	1	.	2	5	.	.	.	.	.	.	.	.	.	.	.	.	8
	ClsMM	.	11	1	25	.	1	4	4	2	.	2	.	2	.	.	14	66
	ClsFR	.	.	3	2	1	3	.	.	.	.	.	.	.	.	.	1	10
	ClsFM	.	2	1	24	4	27	.	9	7	.	2	.	5	.	1	4	86
	FolC	1	.	.	.	.	.	1	.	.	.	1	.	.	.	.	1	4
	FolM	1	5	.	4	.	.	15	5	2	2	14	.	3	.	.	1	52
	FolF	.	.	2	10	.	6	18	26	2	.	10	.	12	.	6	4	96
	SepCM	.	.	.	.	.	.	2	.	.	.	.	.	8	.	.	.	10
	SepMM	.	2	.	2	.	1	7	2	.	1	25	.	1	.	7	.	48
	SepFR	.	.	.	.	.	.	.	.	.	1	1	4	1	.	.	2	9
	SepFM	.	1	1	2	.	2	3	14	6	.	23	6	38	.	4	9	109
	Cruis.	.	1	1	15	.	.	21	33	52	3	72	23	127	11	90	10	459
	Group Total	3	23	11	89	5	40	73	93	72	7	153	33	197	11	108	48	966
ICC at 1sec.	ClsCM	.	4	.	.	.	.	7	.	.	.	.	.	.	.	.	2	13
	ClsMR	1	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	4
	ClsMM	.	20	2	18	.	1	8	7	.	1	7	.	5	.	.	11	80
	ClsFR	.	1	7	3	3	8	2	1	.	.	1	.	.	.	.	2	28
	ClsFM	.	2	3	52	4	52	2	16	5	.	3	.	7	.	2	17	165
	FolC	.	.	.	.	.	.	5	1	.	.	4	.	.	.	.	.	10
	FolM	.	53	.	11	.	.	90	9	2	1	42	1	11	.	3	4	227
	FolF	.	4	.	26	.	11	15	36	7	.	16	.	7	.	2	8	132
	SepCM	.	.	.	.	.	.	2	.	.	.	1	.	2	.	.	.	5
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1	.	3
	SepMM	.	3	.	2	.	.	16	4	.	.	19	.	4	.	4	2	54
	SepFR	.	.	.	.	.	.	.	.	.	.	1	2	5	.	.	1	9
	SepFM	.	2	.	7	.	1	2	11	1	.	19	4	24	.	2	3	76
	Cruis.	.	5	.	19	.	.	18	52	54	1	36	17	51	1	50	7	311
	Group Total	1	94	12	141	7	73	167	137	69	3	149	24	116	3	64	57	1117
ICC at 1.4sec	ClsCM	.	2	.	.	.	.	3	.	.	.	.	.	.	.	.	1	6
	ClsMR	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	3
	ClsMM	.	5	.	9	.	2	5	3	2	1	3	.	3	.	1	2	36
	ClsFR	.	.	3	.	1	6	.	.	1	.	.	.	.	.	.	.	11
	ClsFM	.	2	1	28	.	40	6	13	11	.	8	2	6	.	4	6	127
	FolC	.	.	.	.	.	.	1	1	.	.	2	.	.	.	.	.	4
	FolM	.	13	.	20	.	1	46	16	2	.	32	1	32	.	2	10	175
	FolF	.	7	.	29	.	5	25	56	6	.	23	2	23	1	3	8	188
	SepCR	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	SepCM	.	.	.	.	.	.	1	.	.	.	1	.	1	.	.	.	3
	SepMR	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	SepMM	.	.	.	1	.	.	8	4	.	.	29	1	7	.	4	.	54
	SepFR	.	.	.	.	.	.	.	2	.	.	2	4	5	1	.	3	17
	SepFM	1	2	.	5	1	2	2	18	6	1	32	2	36	2	6	12	128
	Cruis.	.	2	1	17	.	.	12	31	53	5	68	22	128	11	76	14	440
	Group Total	2	33	5	110	2	56	109	144	81	7	202	34	241	15	96	57	1194
ICC at 2sec.	ClsCR	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
	ClsCM	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	ClsMM	.	1	1	.	.	.	.	2	.	.	.	.	1	.	.	.	5
	ClsFR	.	.	1	1	.	1	.	.	.	.	.	.	.	.	.	.	3
	ClsFM	.	.	2	4	.	14	2	2	3	.	1	.	1	.	2	8	39
	FolC	.	.	.	.	.	.	1	.	.	.	2	.	.	.	.	.	3
	FolM	.	.	.	.	.	.	1	1	.	.	.	.	4	.	.	.	6
	FolF	.	1	.	18	1	4	17	41	8	1	37	3	50	.	7	9	197
	SepCM	.	.	.	.	.	.	1	.	.	.	1	.	1	.	.	.	3
	SepMM	.	.	.	.	.	1	2	4	1	1	13	.	10	.	1	.	33
	SepFR	.	.	.	.	.	.	.	.	.	.	3	1	1	.	1	.	6
	SepFM	.	1	.	1	.	.	4	7	7	.	17	2	30	.	2	5	76
	Cruis.	.	1	.	12	.	.	5	9	37	4	27	13	50	7	30	8	203
	Group Total	.	4	4	36	1	20	34	66	56	6	102	19	148	7	43	30	576

Table 3-31 Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode, and the Before/After Driving Sub-States - Freeways

Number of Cut-ins per Hundred Kilometers on Freeways
by Driving Sub-state before and after Cut-in
(ICC Combined)

Before Cut-in		After Cut-in																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Sum	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI
Manual	ClsCR	.	.01	.	.	.	.	.03	.	.00	.	.01	.	.	.	.	.	.05
	ClsCM	.	.08	.	.00	.	.00	.20	.02	.00	.	.05	.	.00	.	.03	.01	.40
	ClsMR	.05	.02	.01	.07	.	.	.01	.01	.	.	.00	.	.00	.	.	.02	.19
	ClsMM	.01	.26	.02	.53	.	.02	.21	.29	.01	.	.05	.	.01	.	.01	.17	1.59
	ClsFR	.	.01	.13	.06	.03	.12	.	.01	.00	.	.	.	.	.	.	.04	.39
	ClsFM	.00	.04	.04	.45	.04	.44	.07	.23	.15	.	.05	.	.05	.	.03	.23	1.81
	FolC	.	.03	.	.01	.	.	.16	.05	.00	.	.05	.	.02	.	.	.01	.33
	FolM	.02	.33	.01	.24	.00	.00	1.66	.21	.03	.00	.37	.00	.15	.01	.02	.07	3.12
	FolF	.01	.08	.02	.31	.00	.21	.45	.88	.17	.	.40	.05	.27	.00	.08	.21	3.14
	SepCM	.	.	.	.	.	.	.04	.	.	.	.00	.	.03	.	.	.	.08
	SepMR	.	.	.	.	.	.	.00	.	.00	.	.00	.01	.03	.02	.	.	.06
	SepMM	.00	.05	.	.01	.	.	.33	.06	.00	.	.55	.	.07	.	.02	.01	1.11
	SepFR	.	.00	.	.00	.	.	.	.	.00	.	.00	.04	.01	.	.02	.00	.08
	SepFM	.	.02	.	.09	.	.05	.21	.30	.10	.02	.33	.02	.58	.	.06	.19	1.96
	Cruis.	.09	.10	.03	.27	.	.	.35	.69	.81	.02	.75	.24	1.43	.15	.83	.16	5.92
	Group Total	.17	1.03	.26	2.03	.07	.85	3.71	2.75	1.29	.04	2.61	.36	2.66	.17	1.09	1.13	20.22
CCC	ClsCR	.	.	.	.	.	.	.	.	.00	.	.	.	.	.	.	.	.00
	ClsCM	.	.00	.	.	.	.	.01	.	.	.	.02	.	.	.	.	.02	.06
	ClsMR	.01	.	.04	.04	.	.	.	.	.	.	.	.	.	.	.	.	.09
	ClsMM	.	.06	.01	.35	.	.02	.03	.04	.02	.	.01	.	.02	.	.	.16	.71
	ClsFR	.	.	.06	.02	.01	.02	.	.	.	.	.	.	.	.	.	.01	.11
	ClsFM	.	.04	.00	.28	.03	.36	.	.07	.09	.	.04	.	.06	.	.00	.05	1.03
	FolC	.03	.	.	.	.	.	.01	.	.	.	.01	.	.	.	.	.01	.06
	FolM	.01	.11	.	.03	.	.	.26	.04	.02	.03	.17	.	.01	.	.	.01	.69
	FolF	.	.	.02	.22	.	.05	.17	.45	.01	.	.11	.	.13	.	.05	.02	1.23
	SepCM	.	.	.	.	.	.	.05	.	.	.	.	.	.19	.	.	.	.23
	SepMM	.	.02	.	.02	.	.01	.08	.02	.	.01	.23	.	.01	.	.15	.	.54
	SepFR	.	.	.	.	.	.	.	.	.	.00	.01	.04	.01	.	.	.01	.07
	SepFM	.	.00	.01	.02	.	.01	.03	.14	.05	.	.31	.06	.42	.	.03	.11	1.19
	Cruis.	.	.01	.01	.16	.	.	.24	.71	.65	.02	.89	.40	1.57	.12	1.04	.21	6.03
	Group Total	.05	.24	.16	1.14	.04	.47	.87	1.47	.84	.07	1.80	.50	2.42	.12	1.28	.60	12.05
ICC Combined	ClsCR	.	.	.	.	.	.	.00	.	.	.	.	.	.	.	.	.	.00
	ClsCM	.	.02	.	.	.	.	.03	.	.	.	.00	.	.	.	.	.01	.06
	ClsMR	.08	.	.	.02	.	.	.	.	.	.	.	.	.	.	.	.01	.11
	ClsMM	.	.10	.01	.05	.	.01	.03	.04	.02	.00	.02	.	.03	.	.00	.05	.37
	ClsFR	.	.00	.11	.02	.02	.06	.00	.00	.00	.	.00	.	.	.	.	.00	.21
	ClsFM	.	.02	.02	.34	.03	.36	.05	.17	.04	.	.04	.00	.03	.	.02	.14	1.26
	FolC	.	.	.	.	.	.	.02	.00	.	.	.03	.	.	.	.	.	.05
	FolM	.	.27	.	.11	.	.00	.37	.09	.00	.00	.27	.00	.15	.	.01	.05	1.34
	FolF	.	.06	.	.41	.00	.06	.28	.49	.08	.00	.64	.01	.39	.01	.02	.13	2.58
	SepCR	.	.	.	.	.	.	.	.	.	.	.00	.	.	.	.	.	.00
	SepCM	.	.	.	.	.	.	.01	.	.	.	.01	.	.02	.	.	.	.04
	SepMR	.	.	.	.	.	.	.	.	.	.	.00	.	.	.01	.00	.	.01
	SepMM	.	.02	.	.01	.	.00	.09	.06	.00	.00	.19	.00	.09	.	.05	.00	.52
	SepFR	.	.	.	.	.	.	.	.00	.	.	.01	.02	.07	.00	.01	.03	.14
	SepFM	.00	.03	.	.03	.00	.00	.01	.10	.05	.00	.24	.03	.55	.00	.03	.06	1.13
	Cruis.	.	.05	.00	.17	.	.	.10	.31	.84	.08	.49	.28	1.09	.07	.56	.11	4.15
	Group Total	.08	.56	.13	1.16	.04	.50	1.00	1.27	1.05	.09	1.94	.34	2.42	.08	.71	.58	11.97

Table 3-32 Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode, ICC Headway Setting and the Before/After Driving Sub-States – Freeways

Number of Cut-ins per Hundred Kilometers on Freeways
by Driving Sub-state before and after Cut-in

Before Cut-in		After Cut-in																Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCR	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI
Manual	ClsCR	.	.01	.	.	.	.	.03	.	.00	.	.01	.	.	.	.	.	.05
	ClsCM	.	.08	.	.00	.	.00	.20	.02	.00	.	.05	.	.00	.	.03	.01	.40
	ClsMR	.05	.02	.01	.07	.	.	.01	.01	.	.	.00	.	.00	.	.	.02	.19
	ClsMM	.01	.26	.02	.53	.	.02	.21	.29	.01	.	.05	.	.01	.	.01	.17	1.59
	ClsFR	.	.01	.13	.06	.03	.12	.	.01	.00	.	.	.	.	.	.	.04	.39
	ClsFM	.00	.04	.04	.45	.04	.44	.07	.23	.15	.	.05	.	.05	.	.03	.23	1.81
	FolC	.	.03	.	.01	.	.	.16	.05	.00	.	.05	.	.02	.	.	.01	.33
	FolM	.02	.33	.01	.24	.00	.00	1.66	.21	.03	.00	.37	.00	.15	.01	.02	.07	3.12
	FolF	.01	.08	.02	.31	.00	.21	.45	.88	.17	.	.40	.05	.27	.00	.08	.21	3.14
	SepCM	.	.	.	.	.	.	.04	.	.	.	.00	.	.03	.	.	.	.08
	SepMR	.	.	.	.	.	.	.00	.	.00	.	.00	.01	.03	.02	.	.	.06
	SepMM	.00	.05	.	.01	.	.	.33	.06	.00	.	.55	.	.07	.	.02	.01	1.11
	SepFR	.	.00	.	.00	.	.	.	.	.00	.	.00	.04	.01	.	.02	.00	.08
	SepFM	.	.02	.	.09	.	.05	.21	.30	.10	.02	.33	.02	.58	.	.06	.19	1.96
	Cruis.	.09	.10	.03	.27	.	.	.35	.69	.81	.02	.75	.24	1.43	.15	.83	.16	5.92
	Group Total	.17	1.03	.26	2.03	.07	.85	3.71	2.75	1.29	.04	2.61	.36	2.66	.17	1.09	1.13	20.22
CCC	ClsCR	.	.	.	.	.	.	.	.	.00	.	.	.	.	.	.	.	.00
	ClsCM	.	.00	.	.	.	.	.01	.	.	.	.02	.	.	.	.	.02	.06
	ClsMR	.01	.	.04	.04	.	.	.	.	.	.	.	.	.	.	.	.	.09
	ClsMM	.	.06	.01	.35	.	.02	.03	.04	.02	.	.01	.	.02	.	.	.16	.71
	ClsFR	.	.	.06	.02	.01	.02	.	.	.	.	.	.	.	.	.	.01	.11
	ClsFM	.	.04	.00	.28	.03	.36	.	.07	.09	.	.04	.	.06	.	.00	.05	1.03
	FolC	.03	.	.	.	.	.	.01	.	.	.	.01	.	.	.	.	.01	.06
	FolM	.01	.11	.	.03	.	.	.26	.04	.02	.03	.17	.	.01	.	.	.01	.69
	FolF	.	.	.02	.22	.	.05	.17	.45	.01	.	.11	.	.13	.	.05	.02	1.23
	SepCM	.	.	.	.	.	.	.05	.	.	.	.	.	.19	.	.	.	.23
	SepMM	.	.02	.	.02	.	.01	.08	.02	.	.01	.23	.	.01	.	.15	.	.54
	SepFR	.	.	.	.	.	.	.	.	.	.00	.01	.04	.01	.	.	.01	.07
	SepFM	.	.00	.01	.02	.	.01	.03	.14	.05	.	.31	.06	.42	.	.03	.11	1.19
	Cruis.	.	.01	.01	.16	.	.	.24	.71	.65	.02	.89	.40	1.57	.12	1.04	.21	6.03
	Group Total	.05	.24	.16	1.14	.04	.47	.87	1.47	.84	.07	1.80	.50	2.42	.12	1.28	.60	12.05
ICC at 1sec.	ClsCM	.	.02	.	.	.	.	.08	.	.	.	.	.	.	.	.	.01	.11
	ClsMR	.00	.	.	.01	.	.	.	.	.	.	.	.	.	.	.	.	.01
	ClsMM	.	.26	.01	.06	.	.01	.04	.04	.	.01	.04	.	.04	.	.	.06	.56
	ClsFR	.	.00	.07	.04	.04	.08	.00	.01	.	.	.00	.	.	.	.	.00	.25
	ClsFM	.	.04	.01	.55	.08	.43	.04	.11	.01	.	.03	.	.05	.	.03	.13	1.50
	FolC	.	.	.	.	.	.	.04	.01	.	.	.07	.	.	.	.	.	.11
	FolM	.	.66	.	.10	.	.	.70	.03	.00	.00	.43	.00	.06	.	.01	.03	2.03
	FolF	.	.12	.	.28	.	.11	.32	.29	.04	.	1.01	.	.12	.	.01	.04	2.35
	SepCM	.	.	.	.	.	.	.01	.	.	.	.01	.	.01	.	.	.	.02
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.00	.	.02
	SepMM	.	.05	.	.02	.	.	.14	.01	.	.	.18	.	.09	.	.04	.01	.54
	SepFR	.	.	.	.	.	.	.	.	.	.	.01	.03	.15	.	.	.04	.23
	SepFM	.	.04	.	.06	.	.01	.01	.06	.00	.	.20	.03	.71	.	.02	.06	1.18
	Cruis.	.	.11	.	.15	.	.	.16	.46	.72	.00	.41	.47	1.13	.04	.55	.04	4.23
	Group Total	.00	1.30	.08	1.27	.12	.64	1.53	1.01	.78	.01	2.38	.53	2.36	.06	.66	.42	13.15
ICC at 1.4sec	ClsCM	.	.03	.	.	.	.	.01	.	.	.	.	.	.	.	.	.01	.05
	ClsMR	.21	.	.	.05	.	.	.	.	.	.	.	.	.	.	.	.03	.28
	ClsMM	.	.02	.	.08	.	.03	.05	.02	.06	.00	.02	.	.04	.	.01	.07	.39
	ClsFR	.	.	.22	.	.00	.07	.	.	.00	.	.	.	.	.	.	.	.29
	ClsFM	.	.01	.00	.35	.	.38	.04	.32	.05	.	.08	.01	.04	.	.02	.09	1.39
	FolC	.	.	.	.	.	.	.01	.00	.	.	.00	.	.	.	.	.	.02
	FolM	.	.12	.	.20	.	.00	.28	.16	.01	.	.33	.01	.27	.	.02	.10	1.49
	FolF	.	.04	.	.18	.	.03	.30	.48	.04	.	.24	.00	.24	.02	.01	.09	1.70
	SepCR	.	.	.	.	.	.	.	.	.	.	.00	.	.	.	.	.	.00
	SepCM	.	.	.	.	.	.	.01	.	.	.	.00	.	.01	.	.	.	.03
	SepMR	.	.	.	.	.	.	.	.	.	.	.01	.	.	.	.	.	.01
	SepMM	.	.	.	.00	.	.	.07	.06	.	.	.24	.00	.03	.	.03	.	.43
	SepFR	.	.	.	.	.	.	.	.01	.	.	.01	.02	.04	.01	.	.04	.12
	SepFM	.01	.03	.	.03	.01	.01	.00	.12	.03	.01	.21	.02	.33	.00	.04	.07	.91
	Cruis.	.	.03	.00	.21	.	.	.09	.28	.47	.06	.54	.22	.95	.09	.74	.20	3.88
	Group Total	.21	.29	.22	1.10	.01	.51	.86	1.45	.66	.07	1.69	.28	1.94	.13	.86	.70	10.99
ICC at 2sec.	ClsCR	.	.	.	.	.	.	.00	.	.	.	.	.	.	.	.	.	.00
	ClsCM	.	.	.	.	.	.	.	.	.	.	.01	.	.	.	.	.	.01
	ClsMM	.	.01	.01	.	.	.	.	.05	.	.	.	.	.01	.	.	.	.09
	ClsFR	.	.	.01	.03	.	.01	.	.	.	.	.	.	.	.	.	.	.05
	ClsFM	.	.	.04	.06	.	.24	.05	.05	.07	.	.01	.	.01	.	.02	.23	.77
	FolC	.	.	.	.	.	.	.02	.	.	.	.01	.	.	.	.	.	.03
	FolM	.	.	.	.	.	.	.10	.07	.	.	.	.	.09	.	.	.	.26
	FolF	.	.01	.	.87	.00	.03	.20	.74	.19	.01	.73	.02	.92	.	.07	.27	4.08
	SepCM	.	.	.	.	.	.	.01	.	.	.	.02	.	.03	.	.	.	.06
	SepMM	.	.	.	.	.	.01	.07	.13	.01	.01	.13	.	.16	.	.11	.	.63
	SepFR	.	.	.	.	.	.	.	.	.	.	.02	.02	.00	.	.02	.	.07
	SepFM	.	.01	.	.01	.	.	.04	.12	.15	.	.33	.02	.67	.	.01	.04	1.38
	Cruis.	.	.01	.	.15	.	.	.04	.18	1.50	.20	.50	.14	1.26	.05	.33	.09	4.45
	Group Total	.	.04	.07	1.12	.00	.29	.54	1.34	1.92	.21	1.75	.19	3.15	.05	.56	.62	11.87

The "before" and "after" sub-states for cut-ins tended to be more distributed compared to lane changes. The prominent "before" sub-states for manual were: *cruising* (25 percent), *following-middle* (17 percent), *following-far* (15 percent), and *closing-far-moderately* (11 percent). The prominent "before" sub-states for CCC were: *cruising* (48 percent), *separating-far-moderately* (11 percent), *following-far* (10 percent), and *closing-far-moderately* (9 percent). The prominent "before" sub-states for ICC were: *cruising* (33 percent), *following-middle* (14 percent), *following-far* (18 percent), and *closing-far-moderately* (11 percent).

The prominent "after" sub-states for manual were: *following-close* (21 percent), *following-middle* (15 percent), *separating-close-moderately* (12 percent), *closing-middle moderately* (11 percent), and s*eparating-middle-moderately* (10 percent). The prominent "after" sub-states for CCC were *separating-middle-moderately* (20 percent), *separating-close-moderately* (16 percent), *separating-far-moderately* (11 percent), and *following-middle* (10 percent). The prominent "after" sub-states for ICC were: *separating-middle-moderately* (17 percent), *separating-close-moderately* (16 percent), *following-middle* (12 percent), and *following-close* (11 percent). The "after" state results are considered slightly safety beneficial for ICC, relative to manual, since the two most prominent "after" states for ICC involve *separating* states whereas they involve *following* states for manual.

There were a substantial number of cut-ins that ended in one of the *close* sub-states, *closing*, *following*, and *separating*, combined. The highest occurrence of these types of cut-ins were for manual (39.5 percent), followed by ICC (31.6 percent), and CCC (26.8 percent). It is interesting that these percentages were all substantially higher, practically double, when compared to lane changes. Part of the explanation is that lane changes are a deliberate action taken on the part of the host driver, whereas cut-ins are actions taken by the other driver. Also, the physical circumstances of a cut-in generally result in a reduction of the previous headway, whereas the opposite is often the case with lane changes. Figure 3-40 summarizes the results in terms of number of cut-ins per hundred kilometers by cruise control mode to each of the five close sub-states. These results suggest a safety benefit for ICC compared to manual. There is a slight safety concern compared to CCC, but most of the *close* states involved the relatively benign states of *separating* and *following*.

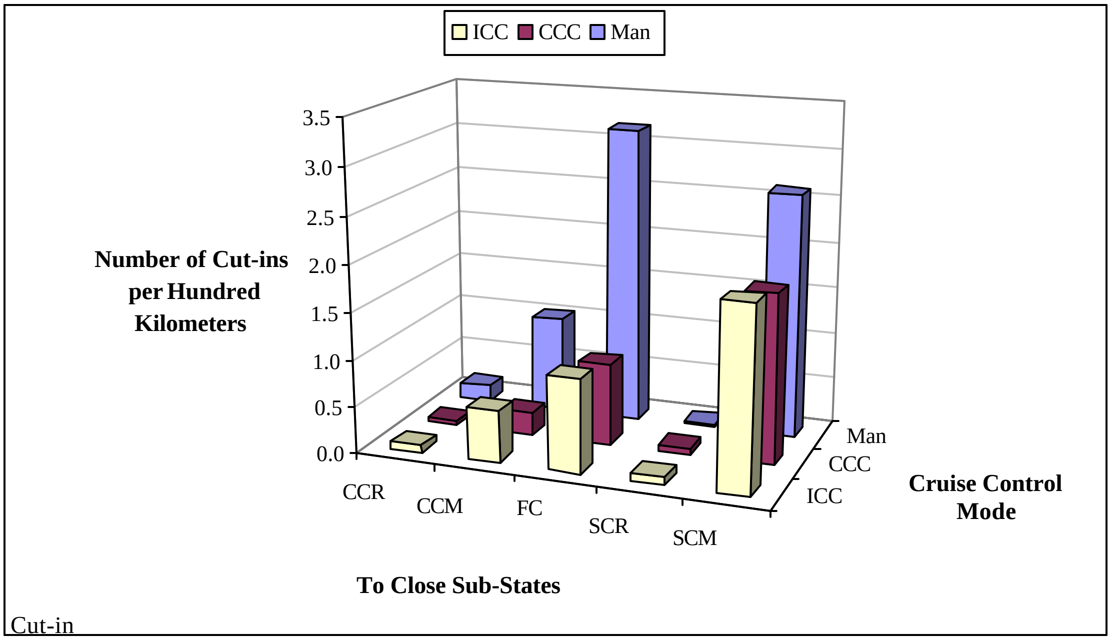

Figure 3-40 Number of Cut-Ins per Hundred Kilometers To Close Sub-States as a Function of Cruise Control Mode - Freeways

There were very few cut-ins <u>to</u> or <u>from</u> the *closing-close-rapidly*, *closing-middle-rapidly and closing-far-rapidly* sub-states. However, the data tends to indicate that cut-ins <u>to</u> the combined states of *closing-close-rapidly*, *closing-middle-rapidly* and *closing-far-rapidly* occurred least often in terms of cut-ins per hundred kilometers for ICC (0.25), and CCC (0.25), and most often for manual (0.50). The rate of cut-ins <u>from</u> the combined states of *closing-close-rapidly*, *closing-middle-rapidly* and *closing-far-rapidly* occurred least often in terms of rate for CCC (0.20), followed by ICC (0.32), and manual (0.63). These results suggest safety benefits for ICC, relative to manual, since any maneuver <u>to</u> or <u>from</u> a closing state is considered safety-critical.

There were a substantial number of cut-ins <u>to</u> or <u>from</u> the *closing-close-moderately*, *closing-middle-moderately and closing-far-moderately* sub-states. Cut-ins <u>from</u> the *closing-close-moderately* and *closing-middle-moderately* sub-states were less for ICC (1.55 percent) compared to manual (3.80 percent) and CCC (1.80 percent). Cut-ins <u>to</u> the *closing-close-moderately*, *closing-middle-moderately* and *closing-far-moderately* sub-states were less for ICC (1.74 percent) compared to manual (3.91 percent) and CCC (1.85 percent). Figure 3-41 summarizes the results in terms of number of cut-ins per hundred kilometers to each of the six closing sub-states by cruise control mode. Again, these results indicate safety benefits for ICC compared to manual and a slight safety concern for ICC compared to CCC.

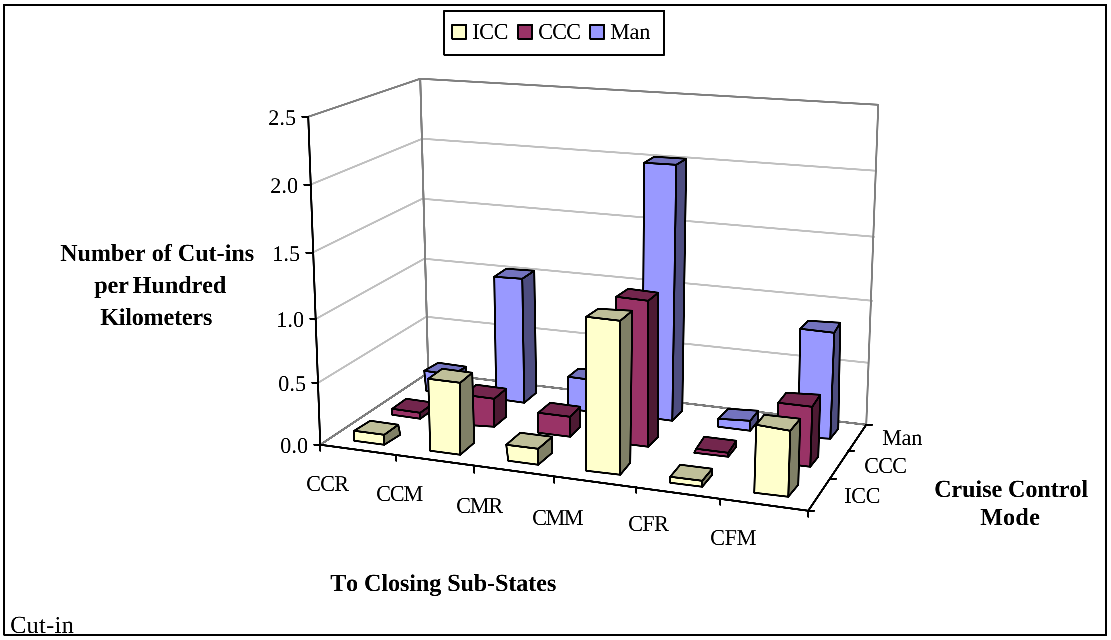

Figure 3-41 Number of Cut-Ins per Hundred kilometers To Closing Sub-States as a Function of Cruise Control Mode - Freeways

There were a substantial number of cut-ins to the *following-close*, *following-middle*, and *following-far* sub-states for each of the modes for comparison. The rate of cut-ins to the *following-close* sub-state was substantially less for ICC (1.00 cut-ins per hundred kilometers) compared to manual (3.71) but slightly more compared to CCC (0.87). The rate of cut-ins to the *following-middle sub-state* was less for ICC (1.27) compared to manual (2.75) and CCC (1.47). The rate of cut-ins to the *following-far* sub-state was less for ICC (1.05) compared to manual (1.29) but slightly more compared to CCC (0.84). A reduction in cut-ins to the *following* sub-states is an indication of safety benefits for ICC.

There were too few cut-ins for ICC and CCC from the *following-close* sub-state for comparison. The rate of cut-ins from the *following-middle* sub-state was less for ICC (1.34 cut-ins per hundred kilometers) compared to manual (3.12) but more compared to CCC (0.69). Cut-ins from the *following-far* sub-state was less for ICC (2.52) compared to manual (3.14) but more compared to CCC (1.23) in terms of the rate. These results are considered safety neutral for ICC, since they all involve relatively benign states of *following-middle* and *-far*.

Summary: The number and pattern of cut-ins indicate a strong safety benefit for ICC compared to manual, and a slight safety concern compared to CCC. There were significantly fewer cut-ins for ICC, and when they did occur, they were less likely than manual to result in any *closing* sub-state, *following-close, or a following-middle* sub-state. Cut-ins did not increase with ICC headway setting.

3.7.10 Cut-Ins on Arterials

The mean number of cut-ins per hundred kilometers is shown in Figure 3-42 as a function of cruise control mode and ICC headway setting. There were significantly fewer cut-ins with ICC and CCC when compared to the number of cut-ins made in the manual mode. The number of cut-ins per hundred kilometers was reduced from approximately 7 for manual to 3 for ICC. There were insufficient data to draw any conclusions from the CCC results.

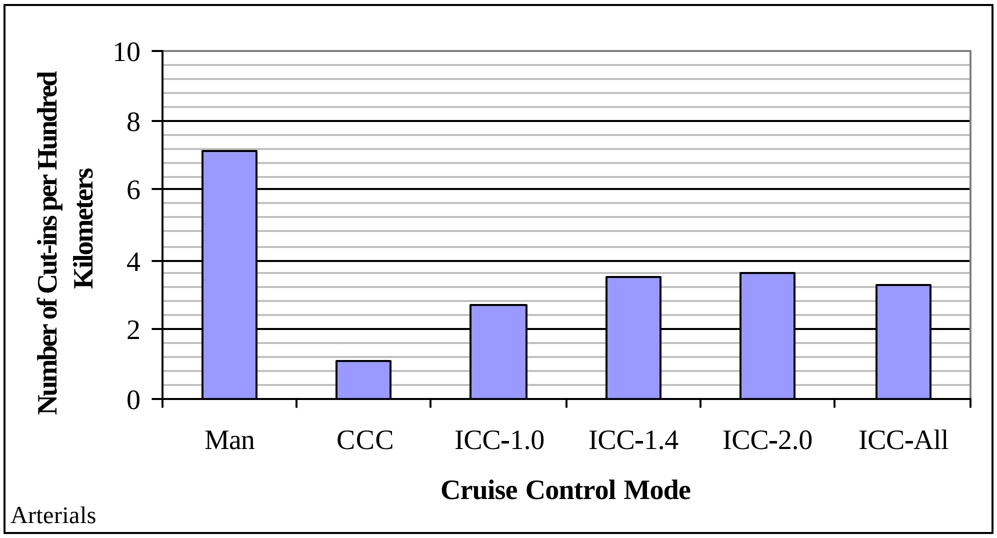

Figure 3-42 Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode and ICC Headway Setting – Arterials

With regard to the ICC headway settings, there were insufficient data to draw any conclusions from the 2.0 second headway setting results and the differences between the 1.0 and 1.4 second headway settings were only marginally significant. There was a slight indication that the number of cut-ins per hundred kilometers increased with headway setting.

Table 3-33 shows the number of cut-ins, and the number of cut-ins per hundred kilometers as a function of cruise control mode and the before/after driving states. Table 3-34 shows similar data as a function of ICC headway settings. In addition to insufficient data for CCC there were insufficient data to draw any conclusions from the state to state results for ICC, either combined or by headway setting.

Based on the limited data, there were marginal indications that ICC had fewer cut-ins both <u>from</u> and <u>to</u> the *closing* state compared to manual, but more cut-ins both <u>from</u> and <u>to</u> the closing state compared to CCC. Relative to manual driving, these results suggest a safety benefit for ICC. The lower rates of cut-ins for CCC relative to ICC may be due, in part, to greater use of ICC in heavier traffic.

Table 3-33 Number of Cut-Ins and the Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode - Arterials

Number of Cut-ins per Hundred Kilometers on Arterials by Driving State before and after Cut-in (ICC Combined)

Before Cut-in		After Cut-in: Closing No. of CI	Closing Rate of CI	Following No. of CI	Following Rate of CI	Separating No. of CI	Separating Rate of CI	Cruising No. of CI	Cruising Rate of CI	Total No. of CI	Total Rate of CI
Manual	Closing	292	1.03	133	.44	34	.12	174	.60	633	2.20
	Following	91	.28	279	.93	47	.20	36	.15	453	1.55
	Separating	8	.04	82	.26	60	.23	16	.05	166	.58
	Cruising	50	.15	276	1.05	291	1.36	73	.26	690	2.82
	Group Total	441	1.51	770	2.68	432	1.90	299	1.06	1942	7.15
CCC	Closing	1	.12	1	.01	.	.	2	.14	4	.28
	Following	1	.07	.	.	.	.	.	.	1	.07
	Separating	.	.	.	.	3	.10	.	.	3	.10
	Cruising	1	.09	2	.05	6	.50	.	.	9	.64
	Group Total	3	.29	3	.07	9	.59	2	.14	17	1.09
ICC Combined	Closing	20	.51	5	.39	.	.	1	.00	26	.90
	Following	3	.11	13	.17	8	.07	4	.29	28	.63
	Separating	.	.	.	.	5	.50	.	.	5	.50
	Cruising	1	.02	14	.46	18	.74	2	.02	35	1.24
	Group Total	24	.64	32	1.02	31	1.31	7	.31	94	3.28

Table 3-34 Number of Cut-Ins and the Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode and the Headway Setting - Arterials

Number of Cut-ins per Hundred Kilometers on Arterials by Driving State before and after Cut-in

Before Cut-in		After Cut-in: Closing No. of CI	Closing Rate of CI	Following No. of CI	Following Rate of CI	Separating No. of CI	Separating Rate of CI	Cruising No. of CI	Cruising Rate of CI	Total No. of CI	Total Rate of CI
Manual	Closing	292	1.03	133	.44	34	.12	174	.60	633	2.20
	Following	91	.28	279	.93	47	.20	36	.15	453	1.55
	Separating	8	.04	82	.26	60	.23	16	.05	166	.58
	Cruising	50	.15	276	1.05	291	1.36	73	.26	690	2.82
	Group Total	441	1.51	770	2.68	432	1.90	299	1.06	1942	7.15
CCC	Closing	1	.12	1	.01	.	.	2	.14	4	.28
	Following	1	.07	.	.	.	.	.	.	1	.07
	Separating	.	.	.	.	3	.10	.	.	3	.10
	Cruising	1	.09	2	.05	6	.50	.	.	9	.64
	Group Total	3	.29	3	.07	9	.59	2	.14	17	1.09
ICC at 1sec.	Closing	9	.77	1	.04	.	.	.	.	10	.81
	Following	1	.06	6	.23	4	.12	1	.69	12	1.10
	Cruising	.	.	4	.36	7	.43	.	.	11	.79
	Group Total	10	.83	11	.63	11	.55	1	.69	33	2.71
ICC at 1.4sec	Closing	10	.63	3	.03	.	.	.	.	13	.67
	Following	2	.22	5	.19	4	.08	1	.03	12	.52
	Separating	.	.	.	.	3	1.20	.	.	3	1.20
	Cruising	.	.	6	.65	7	.41	2	.04	15	1.10
	Group Total	12	.85	14	.88	14	1.69	3	.07	43	3.49
ICC at 2sec.	Closing	1	.04	1	1.26	.	.	1	.02	3	1.32
	Following	.	.	2	.06	.	.	2	.21	4	.27
	Separating	.	.	.	.	2	.10	.	.	2	.10
	Cruising	1	.09	4	.32	4	1.54	.	.	9	1.94
	Group Total	2	.13	7	1.64	6	1.64	3	.22	18	3.63

Tables 3-35 through 3-38 show, respectively, the number of cut-ins as a function of cruise control mode, and the before/after driving sub-states (16x16 matrices); the number of cut-ins as a function of cruise control mode, ICC headway setting, and the before/after driving sub-states; the number of cut-ins per hundred kilometers as a function of cruise control mode and the before/after driving sub-states; and the number of cut-ins per hundred kilometers as a function of cruise control mode, ICC headway setting and the before/after driving sub-states.

As mentioned above, there is insufficient data at these levels to conduct a detailed comparative analysis of the CCC and ICC results.

The pattern of cut-ins overall was roughly the same for ICC and manual. For ICC the main "before" sub-states were *cruising* (37.2 percent), *following* (29.8 percent), and *closing* (27.7 percent), while the main "after" sub-states were *following* (34.0 percent), *separating* (33.0 percent), and *closing* (25.5 percent). For manual, the main "before" sub-states were *cruising* (35.5 percent), *closing* (32.6 percent) and *following* (23.3 percent), while the main "after" sub-states were *following* (34.0 percent), *separating* (33.0 percent), and *closing* (25.5 percent).

Table 3-35 Number of Cut-Ins as a Function of Cruise Control Mode, and the Before/After Driving Sub-States – Arterials

Number of Cut-ins on Arterials
by Driving Sub-state before and after Cut-in
(ICC Combined)

Before Cut-in		After Cut-in															Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
Manual	ClsCR	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	2
	ClsCM	.	2	.	.	.	.	8	3	.	1	.	2	.	.	5	21
	ClsMR	1	2	.	8	.	.	.	2	.	.	.	.	.	1	13	27
	ClsMM	1	17	4	32	.	1	10	38	7	1	.	9	.	2	60	182
	ClsFR	.	1	24	6	2	19	1	2	1	.	.	.	.	3	17	76
	ClsFM	.	5	8	76	9	74	6	31	22	1	.	4	.	10	79	325
	FolC	.	2	.	.	.	.	5	2	.	.	.	.	.	1	.	10
	FolM	.	13	.	13	.	.	86	27	2	3	.	9	.	4	10	167
	FolF	1	11	.	33	1	17	45	101	11	8	.	22	.	.	26	276
	SepCM	.	.	.	.	.	.	.	.	.	1	.	4	.	.	.	5
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	2
	SepMM	.	2	.	.	.	.	12	11	1	3	.	5	.	6	.	40
	SepFR	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1
	SepFM	.	3	.	1	.	2	16	40	2	14	2	19	.	3	16	118
	Cruis.	.	5	4	41	.	.	46	117	113	27	5	158	6	95	73	690
	Group Total	3	63	40	210	12	113	237	374	159	59	7	233	8	125	299	1942
CCC	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
	ClsFM	.	.	1	.	.	.	.	.	1	.	.	.	.	.	1	3
	FolF	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
	SepFR	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	1
	SepFM	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	2
	Cruis.	.	1	.	.	.	.	.	.	2	1	2	3	.	.	.	9
	Group Total	.	1	1	1	.	.	.	.	3	2	3	4	.	.	2	17
ICC Combined	ClsMM	.	1	.	3	.	.	1	2	.	.	.	.	.	.	.	7
	ClsFR	.	.	2	1	.	2	.	.	.	.	.	.	.	.	.	5
	ClsFM	.	.	1	5	1	4	1	.	1	.	.	.	.	.	1	14
	FolC	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	FolM	.	1	.	1	.	1	3	1	.	3	.	2	.	.	.	12
	FolF	.	.	.	.	.	.	.	7	2	1	.	.	.	1	4	15
	SepMM	.	.	.	.	.	.	.	.	.	.	.	2	1	.	.	3
	SepFM	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	2
	Cruis.	.	.	.	1	.	.	2	2	10	.	1	11	.	6	2	35
	Group Total	.	2	3	11	1	7	7	12	13	6	1	16	1	7	7	94

In the manual mode, the main "before/after" cut-ins were as follows: *cruising to separating-middle-moderately* (8.1 percent), *cruising to following-middle* (6.0 percent), *cruising to following-far* (5.8 percent), and *following-far to following-middle* (5.2 percent). Further, in the manual mode, the occurrence of the combined "before" *close* sub-states was 2.0 percent, the combined "before" *closing-close-rapidly* and *closing-middle-rapidly* sub-states was 1.5 percent, the combined "after" *close* sub-states was 18.6 percent, and the combined "after" *closing-close-rapidly* and *closing-middle-rapidly* sub-state was 2.2 percent.

Summary: The number of cut-ins on arterials indicates a strong safety benefit for ICC compared to manual. There were insufficient data to make a comparison with CCC. There were also insufficient data to make a comparison between ICC headway settings. The overall pattern of the cut-ins with respect to the manual and ICC cruise modes seemed to be the same in that the top "before" state was *cruising*, and the top "after" state was *following.* The pattern of cut-ins in terms of the other sub-states with respect to the cruise modes could not be discerned because of the paucity of data. In the manual mode, drivers are much more likely to be in a *close*, *closing-close-rapidly* or *closing-middle-rapidly* sub-state just after a cut-in then they are just before a cut-in.

Table 3-36 Number of Cut-Ins as a Function of Cruise Control Mode, ICC Headway Setting, and the Before/After Driving Sub-States - Arterials

Number of Cut-ins on Arterials
by Driving Sub-state before and after Cut-in

Before Cut-in		After Cut-in															Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
Manual	ClsCR	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	2
	ClsCM	.	2	.	.	.	.	8	3	.	1	.	2	.	.	5	21
	ClsMR	1	2	.	8	.	.	.	2	.	.	.	.	.	1	13	27
	ClsMM	1	17	4	32	.	1	10	38	7	1	.	9	.	2	60	182
	ClsFR	.	1	24	6	2	19	1	2	1	.	.	.	.	3	17	76
	ClsFM	.	5	8	76	9	74	6	31	22	1	.	4	.	10	79	325
	FolC	.	2	.	.	.	.	5	2	.	.	.	.	.	1	.	10
	FolM	.	13	.	13	.	.	86	27	2	3	.	9	.	4	10	167
	FolF	1	11	.	33	1	17	45	101	11	8	.	22	.	.	26	276
	SepCM	.	.	.	.	.	.	.	.	.	1	.	4	.	.	.	5
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	2
	SepMM	.	2	.	.	.	.	12	11	1	3	.	5	.	6	.	40
	SepFR	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1
	SepFM	.	3	.	1	.	2	16	40	2	14	2	19	.	3	16	118
	Cruis.	.	5	4	41	.	.	46	117	113	27	5	158	6	95	73	690
	Group Total	3	63	40	210	12	113	237	374	159	59	7	233	8	125	299	1942
CCC	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
	ClsFM	.	.	1	.	.	.	.	.	1	.	.	.	.	.	1	3
	FolF	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
	SepFR	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	1
	SepFM	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	2
	Cruis.	.	1	.	.	.	.	.	.	2	1	2	3	.	.	.	9
	Group Total	.	1	1	1	.	.	.	.	3	2	3	4	.	.	2	17
ICC at 1sec.	ClsMM	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	2
	ClsFR	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
	ClsFM	.	.	.	2	1	3	1	.	.	.	.	.	.	.	.	7
	FolC	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	FolM	.	1	.	.	.	.	3	1	.	3	.	.	.	.	.	8
	FolF	.	.	.	.	.	.	.	2	.	.	.	.	.	.	1	3
	Cruis.	.	.	.	.	.	.	.	.	4	.	.	6	.	1	.	11
	Group Total	.	1	.	5	1	3	4	3	4	4	.	6	.	1	1	33
ICC at 1.4sec	ClsMM	.	1	.	1	.	.	1	2	.	.	.	.	.	.	.	5
	ClsFR	.	.	2	.	.	1	.	.	.	.	.	.	.	.	.	3
	ClsFM	.	.	1	3	.	1	.	.	.	.	.	.	.	.	.	5
	FolM	.	.	.	1	.	1	.	.	.	.	.	2	.	.	.	4
	FolF	.	.	.	.	.	.	.	4	1	1	.	.	.	1	1	8
	SepMM	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	2
	SepFM	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1
	Cruis.	.	.	.	.	.	.	1	2	3	.	1	3	.	3	2	15
	Group Total	.	1	3	5	.	3	2	8	4	2	1	7	.	4	3	43
ICC at 2sec.	ClsFR	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
	ClsFM	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1	2
	FolF	.	.	.	.	.	.	.	1	1	.	.	.	.	.	2	4
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1
	SepFM	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1
	Cruis.	.	.	.	1	.	.	1	.	3	.	.	2	.	2	.	9
	Group Total	.	.	.	1	.	1	1	1	5	.	.	3	1	2	3	18

Table 3-37 Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode, and the Before/After Driving Sub-States - Arterials

Number of Cut-ins per Hundred Kilometers on Arterials
by Driving Sub-state before and after Cut-in
(ICC Combined)

Before Cut-in		After Cut-in															Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI
Manual	ClsCR	.	.	.	.	.	.	.01	.	.	.	.	.	.	.	.	.01
	ClsCM	.	.02	.	.	.	.	.02	.01	.	.00	.	.01	.	.	.02	.08
	ClsMR	.00	.01	.	.07	.	.	.	.01	.	.	.	.	.	.00	.06	.14
	ClsMM	.00	.05	.01	.09	.	.01	.04	.12	.02	.00	.	.03	.	.01	.21	.58
	ClsFR	.	.01	.11	.01	.01	.08	.00	.01	.01	.	.	.	.	.01	.06	.31
	ClsFM	.	.02	.03	.25	.04	.24	.02	.08	.10	.00	.	.01	.	.03	.25	1.08
	FolC	.	.01	.	.	.	.	.01	.00	.	.	.	.	.	.00	.	.03
	FolM	.	.03	.	.04	.	.	.24	.07	.00	.01	.	.04	.	.01	.05	.51
	FolF	.00	.03	.	.10	.01	.05	.16	.38	.05	.02	.	.11	.	.	.10	1.02
	SepCM	.	.	.	.	.	.	.	.	.	.00	.	.02	.	.	.	.02
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.01	.	.	.01
	SepMM	.	.02	.	.	.	.	.04	.03	.00	.01	.	.03	.	.02	.	.15
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.01	.	.	.	.01
	SepFM	.	.01	.	.00	.	.01	.05	.13	.00	.04	.01	.08	.	.01	.05	.39
	Cruis.	.	.02	.01	.12	.	.	.15	.46	.43	.10	.02	.78	.02	.43	.26	2.82
	Group Total	.00	.21	.17	.68	.05	.39	.76	1.30	.62	.19	.03	1.12	.03	.53	1.06	7.15
CCC	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	ClsFM	.	.	.12	.	.	.	.	.	.01	.	.	.	.	.	.12	.26
	FolF	.	.	.	.07	.	.	.	.	.	.	.	.	.	.	.	.07
	SepFR	.	.	.	.	.	.	.	.	.	.	.02	.	.	.	.	.02
	SepFM	.	.	.	.	.	.	.	.	.	.04	.	.04	.	.	.	.07
	Cruis.	.	.09	.	.	.	.	.	.	.05	.04	.39	.07	.	.	.	.64
	Group Total	.	.09	.12	.07	.	.	.	.	.07	.07	.42	.10	.	.	.14	1.09
ICC Combined	ClsMM	.	.00	.	.22	.	.	.00	.01	.	.	.	.	.	.	.	.24
	ClsFR	.	.	.01	.01	.	.01	.	.	.	.	.	.	.	.	.	.03
	ClsFM	.	.	.03	.03	.02	.17	.01	.	.36	.	.	.	.	.	.00	.64
	FolC	.	.	.	.	.	.	.	.	.	.01	.	.	.	.	.	.01
	FolM	.	.02	.	.07	.	.01	.06	.01	.	.03	.	.01	.	.	.	.21
	FolF	.	.	.	.	.	.	.	.08	.02	.01	.	.	.	.01	.29	.42
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.39	.01	.	.	.40
	SepFM	.	.	.	.	.	.	.	.	.	.08	.	.02	.	.	.	.10
	Cruis.	.	.	.	.02	.	.	.03	.23	.21	.	.08	.22	.	.45	.02	1.24
	Group Total	.	.02	.04	.37	.02	.19	.10	.32	.59	.13	.08	.63	.01	.46	.31	3.28

Table 3-38 Number of Cut-Ins per Hundred Kilometers as a Function of Cruise Control Mode, ICC Headway Setting, and the Before/After Driving Sub-States – Arterials

Number of Cut-ins per Hundred Kilometers on Arterials
by Driving Sub-state before and after Cut-in

Before Cut-in		After Cut-in															Total
		ClsCR	ClsCM	ClsMR	ClsMM	ClsFR	ClsFM	FolC	FolM	FolF	SepCM	SepMR	SepMM	SepFR	SepFM	Cruis.	
		Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI	Rate of CI
Manual	ClsCR	.	.	.	.	.	.	.01	.	.	.	.	.	.	.	.	.01
	ClsCM	.	.02	.	.	.	.	.02	.01	.	.00	.	.01	.	.	.02	.08
	ClsMR	.00	.01	.	.07	.	.	.	.01	.	.	.	.	.	.00	.06	.14
	ClsMM	.00	.05	.01	.09	.	.01	.04	.12	.02	.00	.	.03	.	.01	.21	.58
	ClsFR	.	.01	.11	.01	.01	.08	.00	.01	.01	.	.	.	.	.01	.06	.31
	ClsFM	.	.02	.03	.25	.04	.24	.02	.08	.10	.00	.	.01	.	.03	.25	1.08
	FolC	.	.01	.	.	.	.	.01	.00	.	.	.	.	.	.00	.	.03
	FolM	.	.03	.	.04	.	.	.24	.07	.00	.01	.	.04	.	.01	.05	.51
	FolF	.00	.03	.	.10	.01	.05	.16	.38	.05	.02	.	.11	.	.	.10	1.02
	SepCM	.	.	.	.	.	.	.	.	.	.00	.	.02	.	.	.	.02
	SepMR	.	.	.	.	.	.	.	.	.	.	.	.	.01	.	.	.01
	SepMM	.	.02	.	.	.	.	.04	.03	.00	.01	.	.03	.	.02	.	.15
	SepFR	.	.	.	.	.	.	.	.	.	.	.	.01	.	.	.	.01
	SepFM	.	.01	.	.00	.	.01	.05	.13	.00	.04	.01	.08	.	.01	.05	.39
	Cruis.	.	.02	.01	.12	.	.	.15	.46	.43	.10	.02	.78	.02	.43	.26	2.82
	Group Total	.00	.21	.17	.68	.05	.39	.76	1.30	.62	.19	.03	1.12	.03	.53	1.06	7.15
CCC	ClsFR	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.01	.01
	ClsFM	.	.	.12	.	.	.	.	.	.01	.	.	.	.	.	.12	.26
	FolF	.	.	.	.07	.	.	.	.	.	.	.	.	.	.	.	.07
	SepFR	.	.	.	.	.	.	.	.	.	.	.02	.	.	.	.	.02
	SepFM	.	.	.	.	.	.	.	.	.	.04	.	.04	.	.	.	.07
	Cruis.	.	.09	.	.	.	.	.	.	.05	.04	.39	.07	.	.	.	.64
	Group Total	.	.09	.12	.07	.	.	.	.	.07	.07	.42	.10	.	.	.14	1.09
ICC at 1sec.	ClsMM	.	.	.	.14	.	.	.	.	.	.	.	.	.	.	.	.14
	ClsFR	.	.	.	.02	.	.	.	.	.	.	.	.	.	.	.	.02
	ClsFM	.	.	.	.06	.06	.49	.04	.	.	.	.	.	.	.	.	.65
	FolC	.	.	.	.	.	.	.	.	.	.02	.	.	.	.	.	.02
	FolM	.	.06	.	.	.	.	.18	.02	.	.10	.	.	.	.	.	.35
	FolF	.	.	.	.	.	.	.	.04	.	.	.	.	.	.	.69	.73
	Cruis.	.	.	.	.	.	.	.	.	.36	.	.	.39	.	.05	.	.79
	Group Total	.	.06	.	.22	.06	.49	.22	.06	.36	.12	.	.39	.	.05	.69	2.71
ICC at 1.4sec	ClsMM	.	.00	.	.46	.	.	.01	.02	.	.	.	.	.	.	.	.49
	ClsFR	.	.	.01	.	.	.00	.	.	.	.	.	.	.	.	.	.02
	ClsFM	.	.	.09	.04	.	.03	.	.	.	.	.	.	.	.	.	.16
	FolM	.	.	.	.19	.	.03	.	.	.	.	.	.02	.	.	.	.24
	FolF	.	.	.	.	.	.	.	.16	.03	.03	.	.	.	.03	.03	.28
	SepMM	.	.	.	.	.	.	.	.	.	.	.	1.00	.	.	.	1.00
	SepFM	.	.	.	.	.	.	.	.	.	.20	.	.	.	.	.	.20
	Cruis.	.	.	.	.	.	.	.03	.57	.05	.	.20	.18	.	.03	.04	1.10
	Group Total	.	.00	.10	.69	.	.06	.04	.76	.08	.23	.20	1.19	.	.06	.07	3.49
ICC at 2sec.	ClsFR	.	.	.	.	.	.04	.	.	.	.	.	.	.	.	.	.04
	ClsFM	.	.	.	.	.	.	.	.	1.26	.	.	.	.	.	.02	1.28
	FolF	.	.	.	.	.	.	.	.02	.04	.	.	.	.	.	.21	.27
	SepMM	.	.	.	.	.	.	.	.	.	.	.	.	.04	.	.	.04
	SepFM	.	.	.	.	.	.	.	.	.	.	.	.06	.	.	.	.06
	Cruis.	.	.	.	.09	.	.	.07	.	.25	.	.	.09	.	1.45	.	1.94
	Group Total	.	.	.	.09	.	.04	.07	.02	1.56	.	.	.14	.04	1.45	.22	3.63

3.8 Overall Driving Behavior

This section presents results from analyses of various safety surrogate measures to estimate how drivers perform using the ICC system over all driving situations. These driving situations encompass all the various states and transitions on freeways and arterials.

3.8.1 Time-Headway

3.8.1.1 Time-Headway on Freeways. To determine whether mode of driving affected the average headway drivers maintained on freeways, an analysis was performed on time-headway as a function of cruise control mode, age group, and duration of participation. For each mode, mean time-headway was computed for each driver. Mean time-headway was computed by averaging headway for each second that (1) a driver was in a particular mode, (2) on a freeway, and (3) for which a preceding vehicle range was reported by the ICC system. Thus, mean time-headway in this evaluation is a measure of the separation from the front bumper of the host vehicle to the rear of the preceding vehicle within the sensor range.

Because not all drivers used all three ICC cruise control headway settings (1.0, 1.4, and 2.0 seconds) most analyses did not discriminate by headway setting. Drivers who had less than five minutes total freeway exposure (summed over trips) with a preceding vehicle present in each mode were also excluded from the time-headway analysis. But a driver that spent at least five minutes, for example, in the ICC 1.0 second headway setting, summed over trips, would be included, even if that driver did not use, or had limited use, of the other headway settings. Initial screening of the headway data revealed a few drivers who never used the ICC at a particular headway setting for more than a few seconds (typically 1 to 5 seconds, but occasionally for 30 to 40 seconds) before disengaging the ICC system. When these very short usage periods occurred, there was either no preceding vehicle, or the preceding vehicle was at a very long headway (three to four seconds). Only a few drivers had these very short usage periods, but those that did typically had several, and also never used the setting in question for any length of time (e.g., longer than two minutes). The five-minute criterion was a convenient way to screen out multiple short usage intervals that were possibly inadvertent on the part of the user. The effect of not screening this data would have been to considerably lengthen average headway with ICC and CCC.

There were 73 drivers for whom valid data were available for this analysis. Drivers not included in this analysis, either did not drive on a freeway, did not drive on freeways for longer than 5 minutes in manual, CCC, and ICC modes, or, for one case, did not have GPS data that enabled identification of road class.

As can be seen in Figure 3-43, drivers had the longest average headway when using conventional cruise control and the shortest average headway when using manual control. Average headway when ICC was engaged was intermediate between manual driving and conventional cruise control. The three means shown in Figure 3-43 (1.7 seconds, manual; 1.9 seconds, ICC; 2.2 seconds, CCC) are significantly different from each other. Manual control during the first week is shown as the baseline condition because most driving during the first week was in manual mode, whereas driving in manual mode when

ICC was available appeared to be atypical of conditions under which ICC would be used. That is, when ICC was available, manual control was exercised primarily in heavy and congested traffic conditions (see figure 3-16). Whereas, when CCC was available, manual control was used fairly extensively for all traffic conditions including about 50 percent during light traffic and 67 percent during moderate traffic. Furthermore, CCC was used far less in the first week than ICC was in later weeks, making manual driving during the first week a better comparison condition.

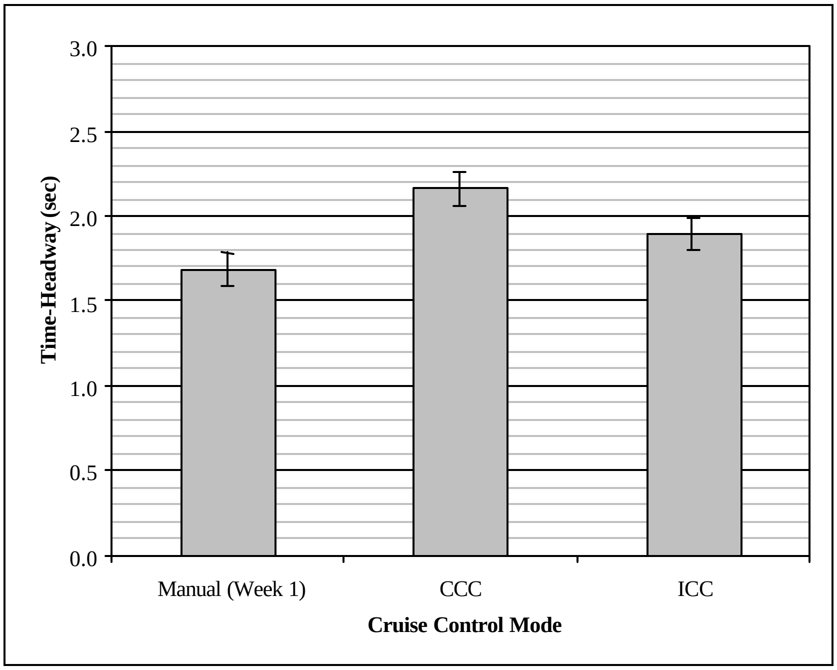

Figure 3-43 Time-Headway on Freeways as a Function of Cruise Control Mode (N = 73)

Figure 3-44 shows the average time-headway for the individual ICC cruise control headway settings. It can be seen that selection of the 1.0 second headway setting was associated with an average headway that is not significantly different from that obtained with manual driving. The 1.4 second headway setting was associated with an average nearly equal to the overall ICC average time-headway. The 2.0 second headway setting was associated with an average time-headway significantly longer than the average observed with conventional cruise control. For all headway settings, the actual average headways were greater than the set value, however, this difference diminishes with longer settings. As will be seen in the next section, part of the explanation for the differences may be attributed to the velocities driven in the different modes. Furthermore, for a fixed headway setting, the time spent above that headway setting when approaching a slower moving vehicle, when being passed by another vehicle, and when adjusting to variations in velocity of a lead vehicle is greater than the time spent below that headway setting for similar circumstances. For a higher headway setting, the ICC system tends to achieve the setting for the approach and velocity adjustment circumstances but provides more opportunities for actual headway to be less than the set headway (e.g., cut-ins) thus tempering the longer setting effect.

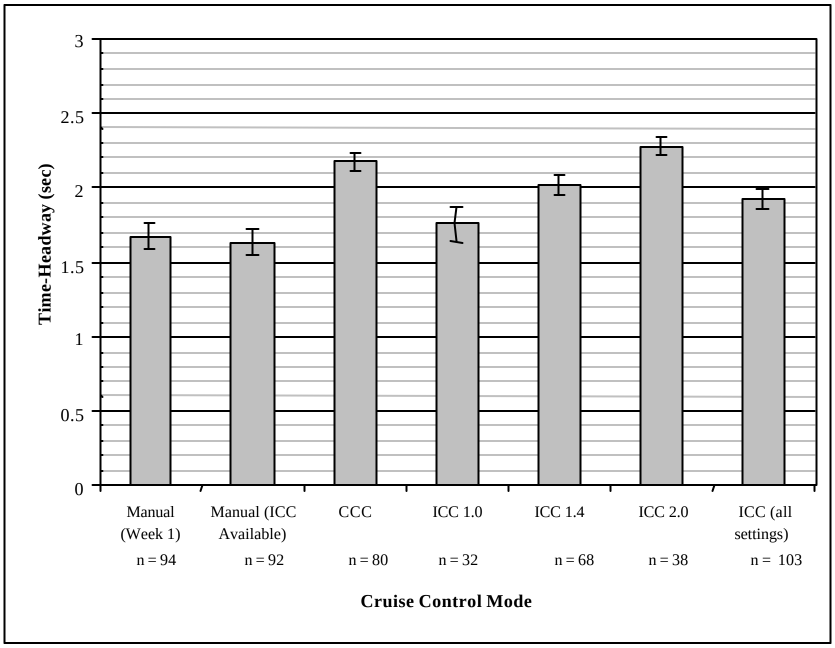

Figure 3-44 Average Time-Headway on Freeways as a Function of Cruise Control Mode and ICC Headway Setting

Figure 3-45 shows the time-headway distributions for the three cruise modes and Figure 3-46 shows the time headway distributions for the three ICC headway settings. Manual headway was 1.0 second or less for about 35 percent of the time, while both CCC and ICC headways were 1.0 second or less for only 10 percent of the time. Both manual and ICC had headways between 1.0 and 1.5 seconds about 25 percent of the time; CCC was about 18 percent. Figure 3-46 indicates the degree to which actual headways aligned with set headways. For the 1.0 second headway setting, actual headways were between 0.5 and 1.5 seconds 55 percent of the time; for the 1.4 second setting they were between 1.0 and 2.0 seconds 56 percent of the time; and for the 2.0 second setting they were between 1.5 and 2.5 seconds 64 percent of the time. Note that drivers who used the 2.0 second headway setting were seldom (less than 10 percent of the time) within 1.5 seconds of a preceding vehicle. These results are consistent with the results found in Section 3.7.5 on driving states and sub-states. From Table 3-8, manual drivers spent more time in the following-close sub-state, whereas manual drivers and ICC drivers spent more time in the following-middle sub-state. From Table 3-9, ICC drivers with a time headway setting of 1.0 second spent more time in the following-close sub-state, those with a 1.0 second or 1.4 second headway setting spent more time in the following-middle sub-state and those with a 2.0 second headway setting spent more time in the following-far sub-state.

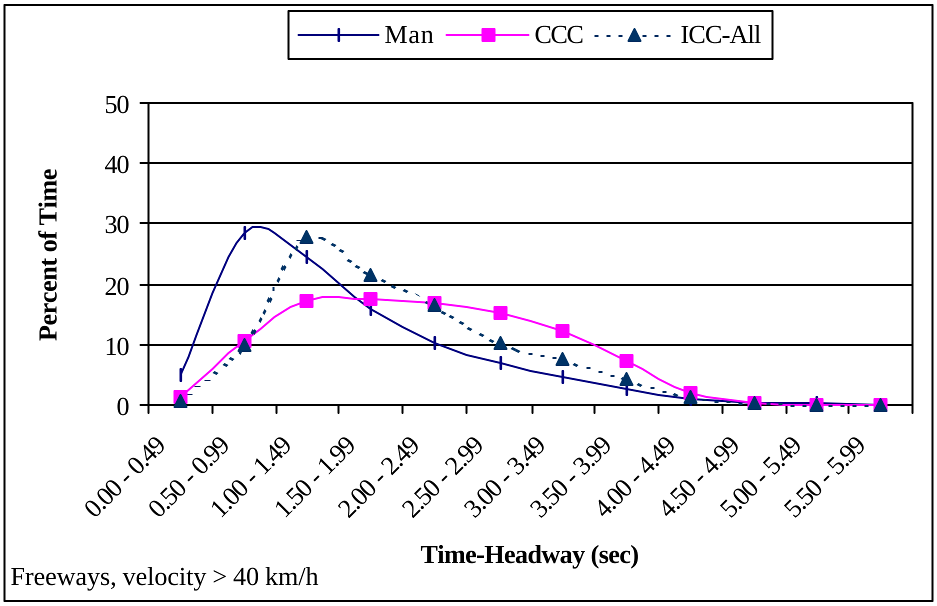

Figure 3-45 Percentage of Time on Freeways as a Function of Time-Headway and Cruise Control Mode

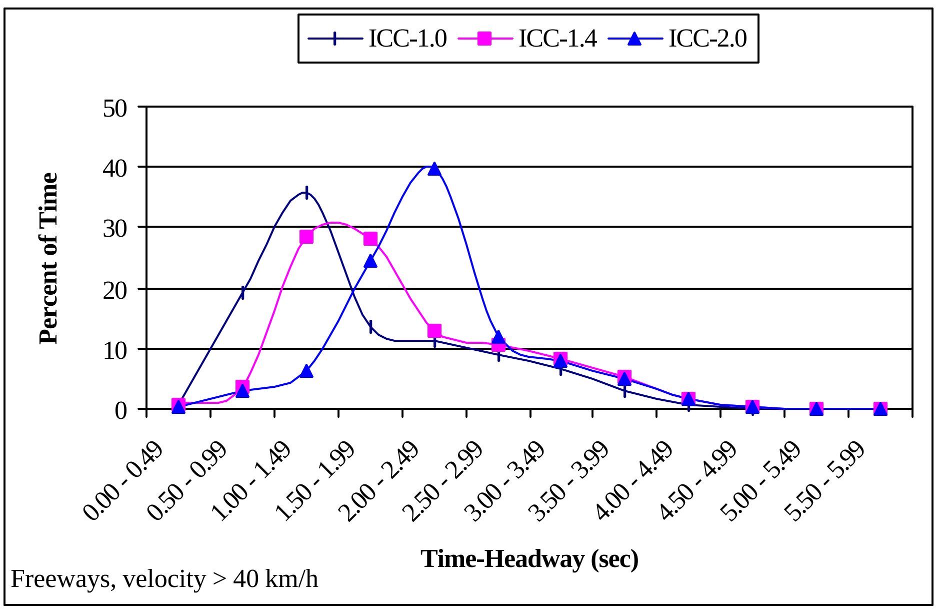

Figure 3-46 Percentage of Time on Freeways as a Function of Time-Headway and ICC Headway Setting

Figure 3-47 shows that older drivers tended to choose the longer ICC headway setting, and tended to maintain longer than average headway in all modes, F (2, 67) = 9.42, $p < 0.01$. Figure 3-47 also indicates that as driver age increased, so did average freeway time-headway. However, older drivers who were recruited to participate for five weeks (n = 7), maintained shorter average headway than the older drivers in the two week group (n = 16), and maintained time-headway similar to the middle-aged drivers. This interaction of age and duration of participation, was statistically reliable, $F(2, 67) = 3.16$, $p < 0.05$, and was essentially the same whether the drivers used ICC, CCC, or manual control. The five-week participants were all prior cruise control users, whereas only half of the two-week participants were prior cruise control users.

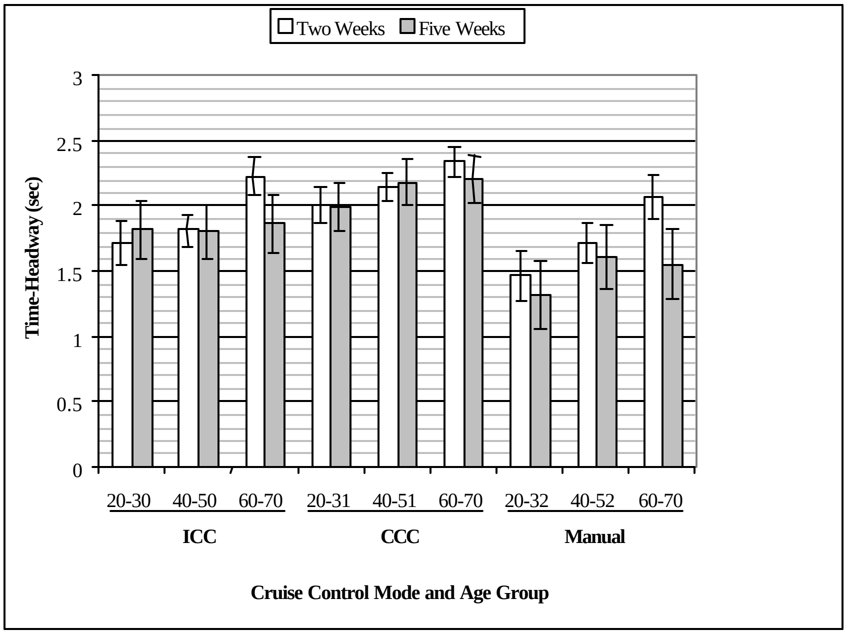

Figure 3-47 Time-Headway as a Function of Cruise Control Mode, Age Group, and Weeks of Participation

Although time-headway had no tendency to vary with prior cruise control use in general, it is possible that the older drivers who do not use cruise control were more conservative in their driving than older drivers who did. The FOT recruiters went outside their normal recruitment procedure, and advertised in local papers to attract a sufficient number of older nonusers of cruise control, and this deviation might have recruited from a different population of drivers than those who responded to post cards. Previous use of cruise control was not related to mean time headway except among the older drivers, however, previous cruise usage did interact with age, $F(2, 67) = 4.61$, $p < 0.05$. Older drivers who said they were not previous users of cruise control maintained significantly longer time-headways than the older drivers who stated that they previously used cruise control.

Figure 3-48 shows time-headway on freeways as a function of velocity. Although below 80 km/h, travel on freeways was likely to have been impeded by traffic, Figure 3-48 suggests that the average time-headway findings reported above hold across the velocity range. That is, ICC with 1.0 second and 1.4 second time-headway selections tend to yield average headways that bracket the headways observed with manual control. The 2.0 second headway setting yields headways longer than those observed with manual driving. It can also be seen that at the highest velocity ranges, above 112 km/h, even ICC with a 1 second headway selection, tends to yield longer average time-headway than is observed with manual control.

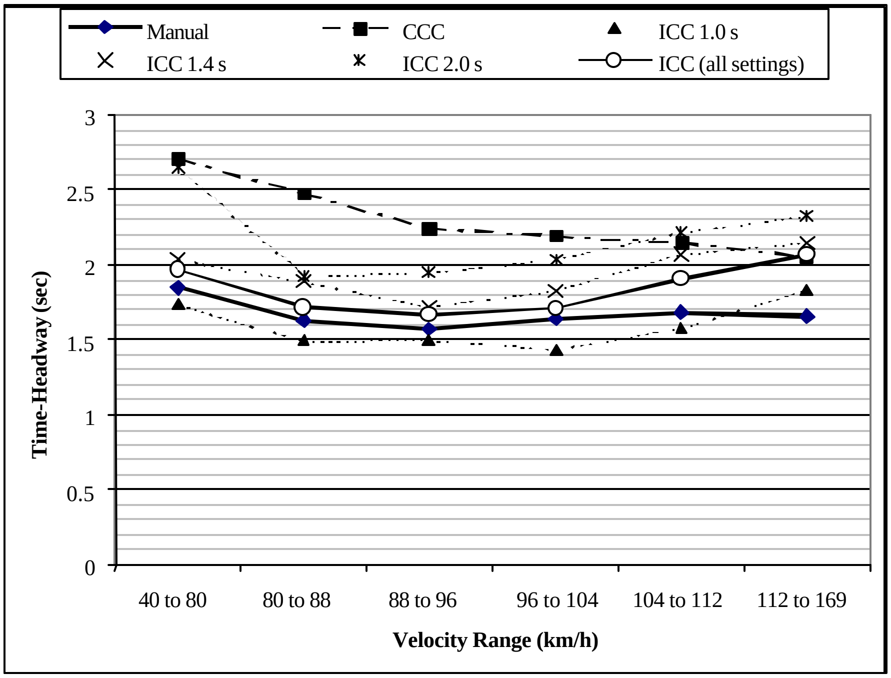

Figure 3-48 Time-Headway on Freeways as a Function of Velocity and Cruise Control Mode

3.8.1.2 Time-Headway on Arterials. Mean time-headway on arterials is shown as a function of cruise control mode and age group in Figure 3-49. Mean time-headway on arterials was considerably longer than on freeways. This result is perhaps more an artifact of the sensor system than a reflection of actual time headways because the sensor range was fixed. Therefore, at lower velocities, the data acquisition system was capable of measuring longer time headways. For example, at 40 km/h the system could record time-headway two times as large as the time-headway it could record at 80 km/h. The arterial results are therefore not directly comparable to the freeway results but are presented here for examining relative differences between modes.

Cruise mode had a significant effect on time-headway, F (2, 46) = 26.40, $p < 0.001$. Whereas, the difference in time-headway between manual driving and driving with CCC was statistically reliable, the difference between ICC and the other two modes was not statistically reliable. However, as for freeways, ICC time-headway (averaged over headway settings) was intermediate between manual and CCC.

As on freeways, older drivers maintained significantly longer time-headways on arterials than the middle-aged and younger drivers, F (2 , 46) = 4.33, $p < 0.05$.

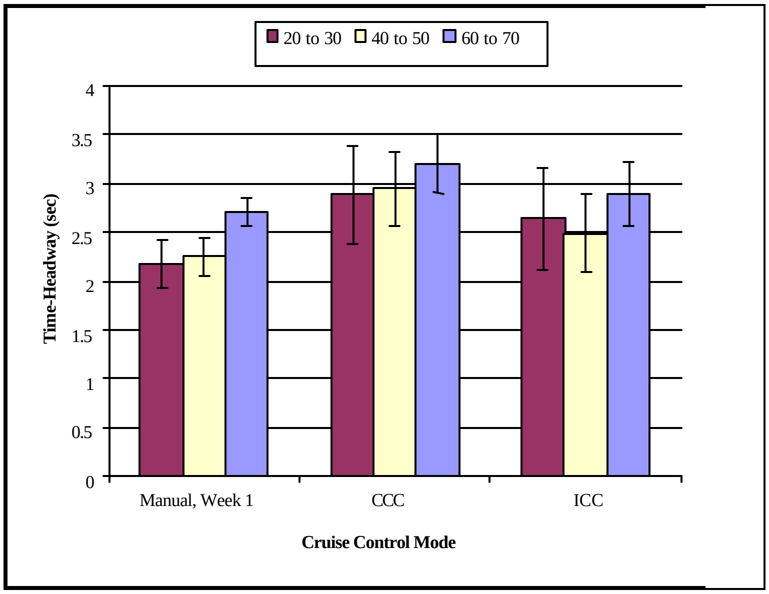

Figure 3-49 Time-Headway on Arterials as a Function of Age Group and Cruise Control Mode (N = 52)

Figure 3-50 shows the time-headway distributions for the three cruise modes and Figure 3-51 shows the time-headway distributions for the three ICC headway settings. The occurrence of lower headways (less than 1.5 seconds) was substantially less on arterials than on freeways (for velocities greater than 40 km/h). Manual headways were 1.0 second or less for only about 10 percent of the time (contrasted with 35 percent on freeways), while both CCC and ICC headways were 1.0 second or less for only 5 percent of the time (10 percent on freeways). Headways for manual driving were between 1.0 and 1.5 seconds about 22 percent of the time, for CCC 18 percent, and for ICC only 10 percent.

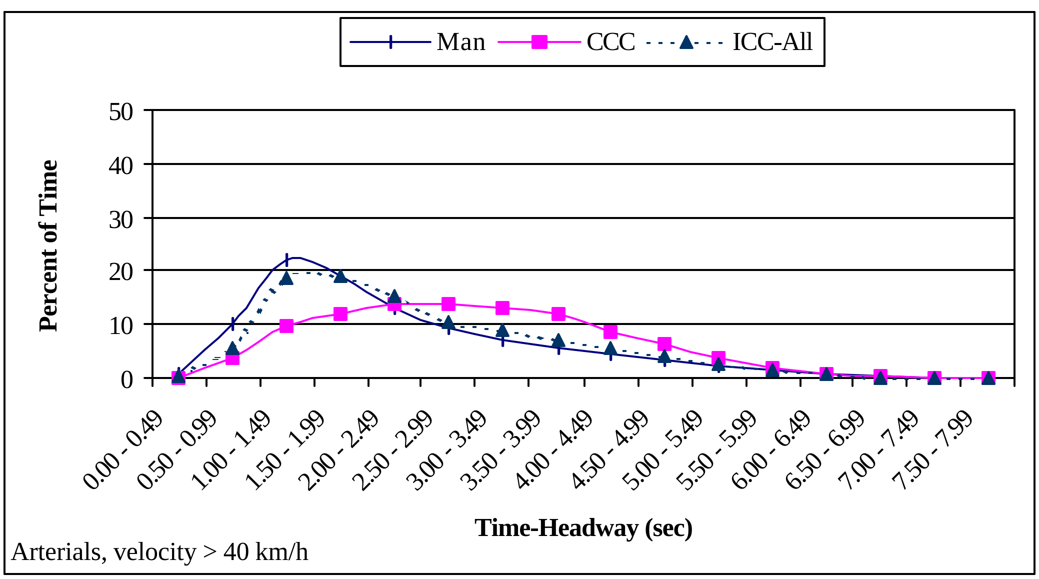

Figure 3-50 Percentage of Time on Arterials as a Function of Time-Headway and Cruise Control Mode

Figure 3-51 shows that for the 1.0 second headway setting, actual headways were between 0.5 and 1.5 seconds 36 percent of the time; for the 1.4 second setting they were between 1.0 and 2.0 seconds 43 percent of the time; and for the 2.0 second setting they were between 1.5 and 2.5 seconds 50 percent of the time. Compared to freeway driving, the actual headways on arterials were more spread out. Similarly to what occurred on freeways, drivers on arterials who used the 2.0 second headway setting were seldom (less than 8 percent of the time) within 1.5 seconds of a preceding vehicle.

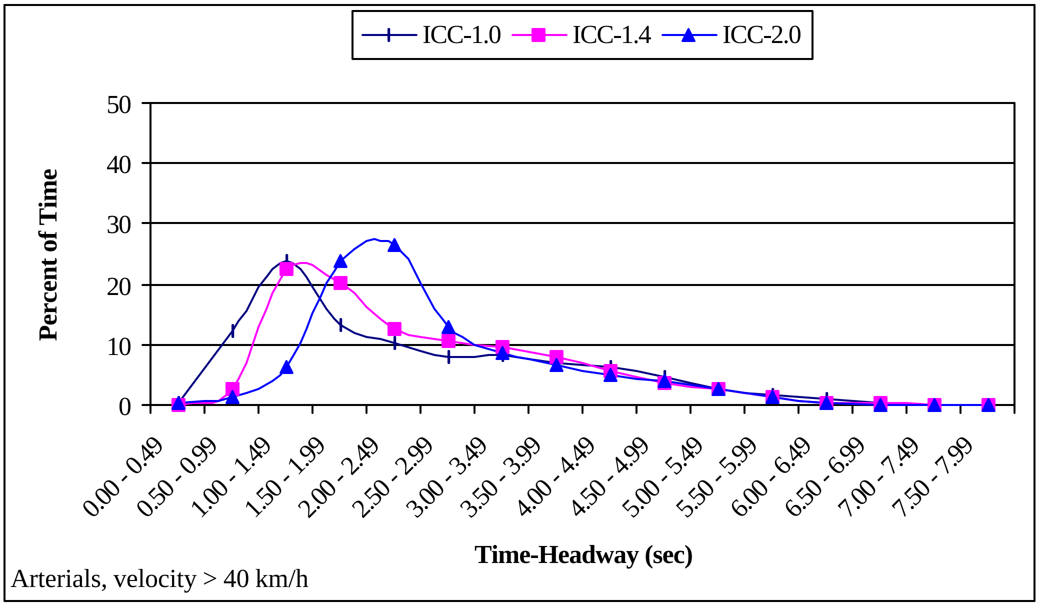

Figure 3-51 Percentage of Time on Arterials as a Function of Time-Headway and ICC Headway Setting

3.8.1.3 Time-Headway on Other Roadways. On roads classified as state highways, only 15 drivers followed another vehicle with ICC enabled for more than 5 minutes. Therefore, the time-headway results for state highways are not presented here.

Roadway classification was not performed for data collected outside of 11 counties in Southeastern Michigan. However, time-headway trends on roadways that were not classified were similar to the trends on freeways, except that only the effect of cruise control mode was statistically reliable. Outside the 11 county area, only 47 drivers provided more than 5 minutes of driving in each of the cruise modes (manual, CCC, and ICC). Therefore, the fact that age group, previous cruise control use, and duration of participation did not yield statistically reliable effects outside the area, as they did for freeway driving, may be attributable to a combination of smaller level of effect and smaller sample size.

3.8.1.4 Time-Headway Summary. In summary, the longer time-headways associated with ICC use are expected to yield a modest safety benefit relative to manual control. On freeways, the potential time-headway safety benefit appears to hold across a wide range of velocities, and may increase slightly at higher velocities. However, velocity, and variability in velocity are two factors that might not remain constant with mode, and these are examined next.

3.8.2 Velocity and Velocity Variability

3.8.2.1 Velocity on Freeways. As can be seen in Figure 3-52, average velocity on freeways was highest when conventional cruise control was selected, slightly, but significantly, less when ICC was selected, and considerably lower in manual mode. The overall relationship of mode to velocity was statistically significant, F (2, 67) = 109.5, $p < 0.001$. The mean velocity for manual driving in Figure 3-52 is from the first week of driving when CCC was available.

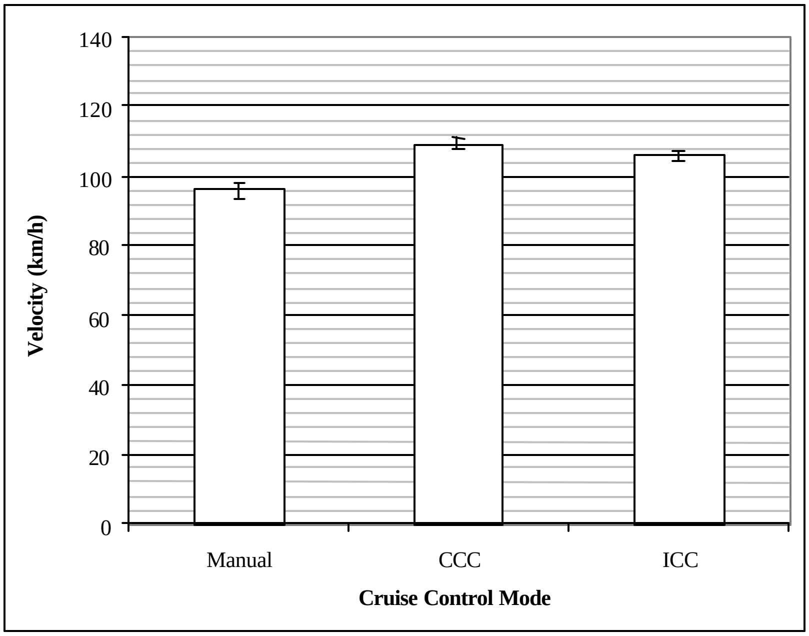

Figure 3-52 Velocity on Freeways as a Function of Cruise Control Mode

As can be seen in Figure 3-53, mean manual velocity on freeways was slightly higher when CCC was available than when ICC was available, t (83) = 4.1, $p < 0.001$. The level of service data presented in Figure 3-15 indicates that ICC and CCC were used primarily when levels of service A or B prevailed (i.e., traffic was light). Furthermore, ICC was used with lower levels of service (C and D) more than CCC. Thus the lower mean velocities in manual, when CCC was available, compared to the CCC mean velocities during week 1, may have been because when traffic was encountered the drivers switched to manual control. When ICC was available and drivers encountered traffic, they appear to have kept the cruise control on longer before disengaging. With average congestion higher in the manual mode, the net result was lower average manual velocities when ICC was available.

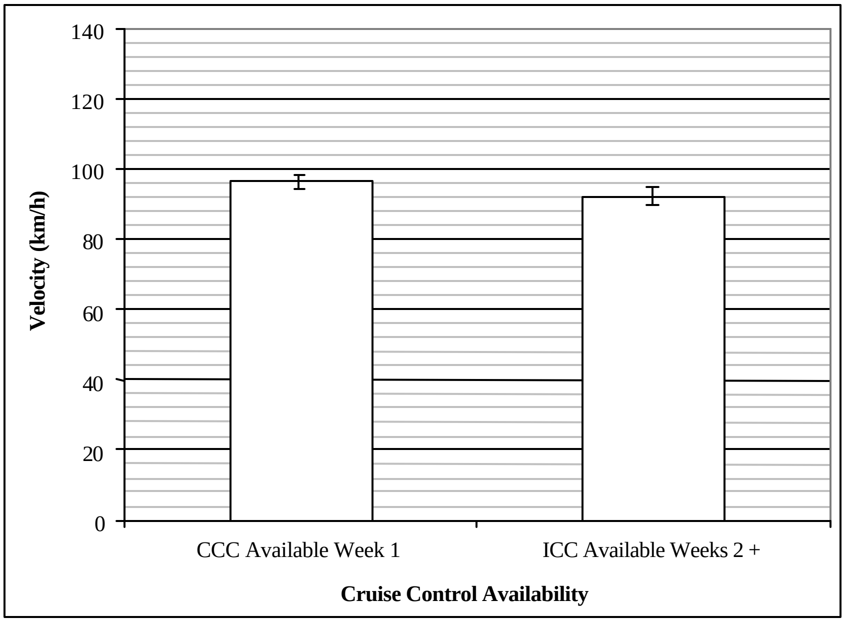

Figure 3-53 Mean Velocity for Manual Driving on Freeways

Figure 3-54 further illustrates why mean travel velocities were lower with manual control than they were with ICC, and why mean ICC travel velocities were lower than mean CCC travel velocities. The figure shows the proportion of driving time in each of twelve 5-mi/h velocity ranges between 40 km/h and 136 km/h. It can be seen that a considerable amount of manual driving (11.5 percent) was below 80 km/h. As this was freeway driving, Figure 3-18 indicates that most of the low velocity driving was the result of congestion. Only 1.9 percent of ICC driving was below 80 km/h, and 0.5 percent of CCC driving was in that range.

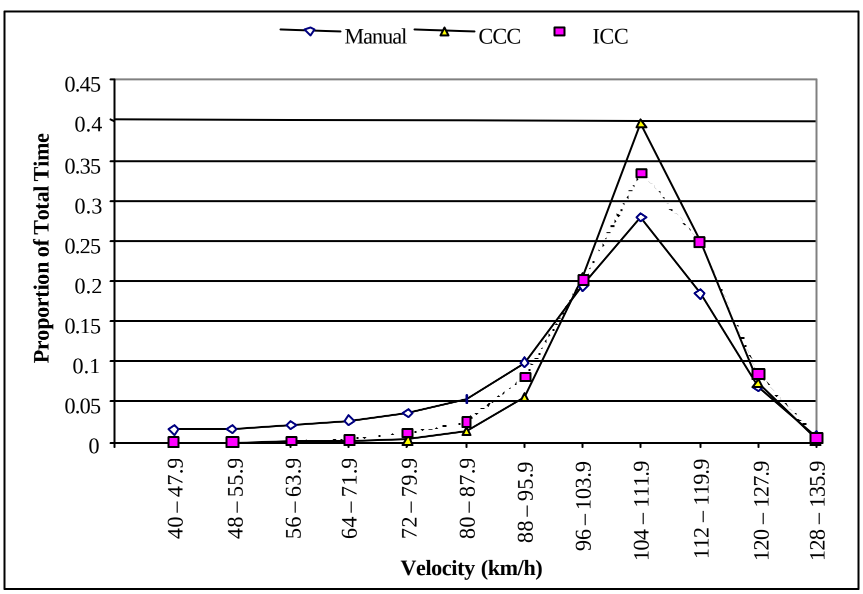

Figure 3-54 Proportion of Driving Time Displayed as a Function of Travel Velocity and Cruise Control Mode

From a velocity perspective, most of the improved ICC functionality over CCC can be seen between 64 and 104 km/h. The improvement appears in Figure 3-54 as the area between the CCC and ICC curves that is to the left of where the curves intersect. In this region ICC was used more than CCC presumably because ICC automatically adjusted to the lower velocity traffic. Between 64 and 104 km/h the percentage of driving for manual, ICC and CCC were 42, 33 and 23 respectively.

The peak of the three velocity histograms is between 104 and 112 km/h. This suggests that in all modes drivers were generally seeking the same velocity.

For ICC to differ in operation from CCC, it was necessary to follow a preceding vehicle that was traveling less than the ICC vehicle's set velocity. One concern of the evaluators, was that ICC users might frequently choose a very high set velocity so that they could observe the system working. As is shown in the next section, drivers did chose slightly higher set velocities with ICC compared to CCC. However, as ICC average velocities were below those of CCC, the concern that ICC might encourage higher average velocities appears to have been unfounded.

In Figure 3-55, it can be seen that average velocity did not vary significantly as a function of cruise control headway setting. However, Figure 3-56, which shows the velocity distributions for the three ICC headway settings, indicates that drivers who used the 1.0 second setting tended to drive at higher velocities (greater than 112 km/h over 53 percent of the time and greater than 120 km/h over 15 percent of the time), and drivers who used the 2.0 second setting tended to drive at lower velocities (less than 96 km/h over 12 percent of the time).

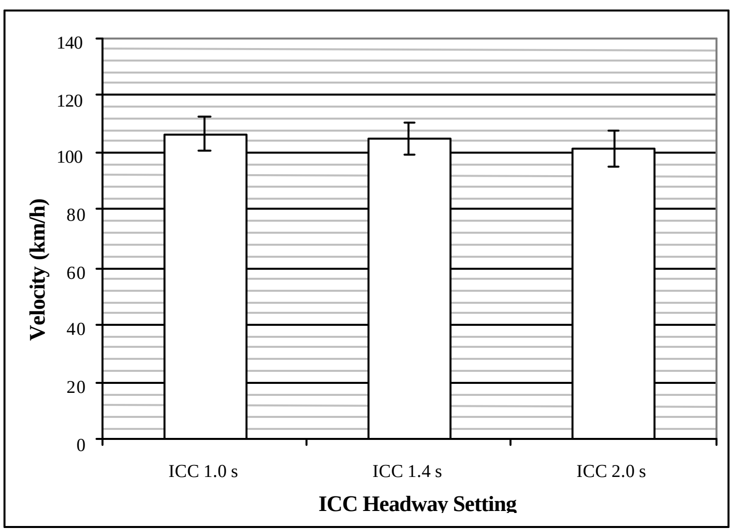

Figure 3-55 Average Freeway Velocity as a Function of ICC Headway Setting

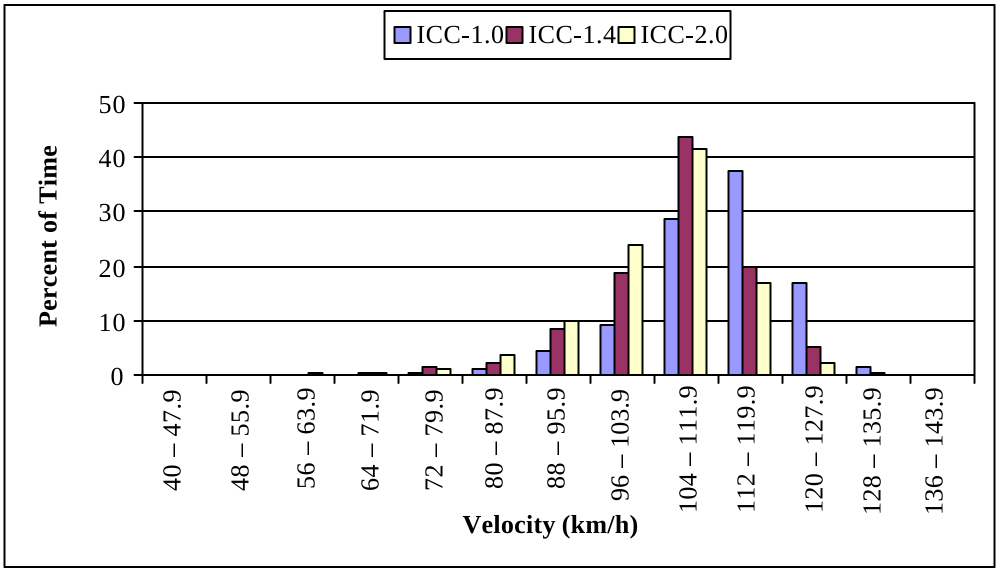

Figure 3-56 Percentage of Time on Freeways as a Function of Travel Velocity and ICC Headway Setting

Besides cruise mode, the only other factor that was significantly related to velocity was age group, $F\ (2, 67) = 7.46$, $p < 0.01$. As can be seen in Figure 3-57, the youngest age group drove significantly faster than the two older groups, and the older group drove somewhat slower than the middle-aged group. In both cases, the differences were not substantial, i.e., they were less than 8 km/h.

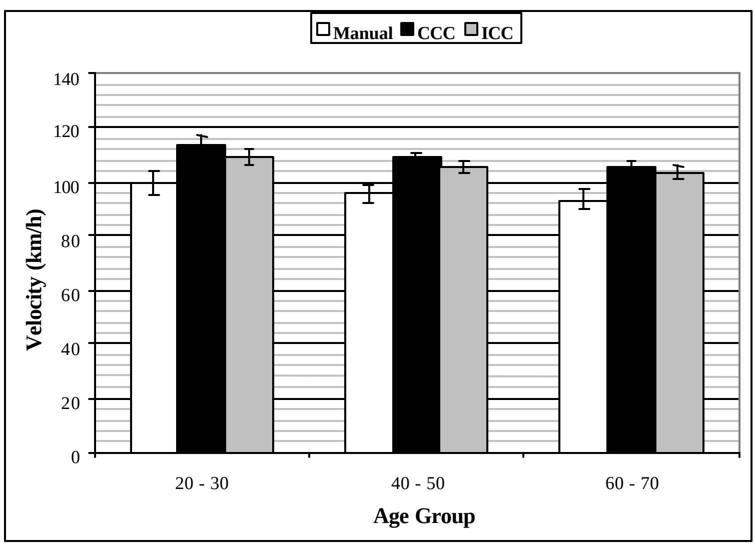

Figure 3-57 Velocity on Freeways as a Function of Age Group and Cruise Control Mode.

3.8.2.2 Velocity Variability on Freeways. When drivers used cruise control, their velocity variability was considerably less than when they drove manually. Velocity variability on freeways, as a function of cruise control mode, is shown in Figure 3-58. The data shown in Figure 3-58 represent the standard deviation in second by second velocity for all trips on freeways. For each trip the driver had to remain in a mode for at least 30 seconds in order for the data to be included. The 30-second restriction was included because the standard deviation of a mean tends to approximate the population standard deviation when *n* approaches 30. Each driver contributed only one standard deviation for each mode. Where drivers had more than one trip in a mode, the value used in the analysis was the unweighted mean standard deviation across trips. Only velocities above 40 km/h were considered in the computation of the standard deviation because ICC and CCC did not operate below 40 km/h.

In a review article, Warren (1982) cites a number of studies that suggest velocity variability is associated with increased crash and injury rates. However, Warren's findings were with respect to the number of vehicles deviating from the mean velocity for a roadway segment, not to changes in the velocity of individual vehicles. However, it may not be unreasonable to assume that the individual vehicle velocity fluctuations measured here can be associated with an increased probability of rear-end collisions. Additionally, from a pre-crash dynamics perspective (see Section 3.11), greater variations in velocity of one vehicle among several vehicles increases the probability that two vehicles with large closing rates will encounter one another and be involved in a rear-end collision. Thus the tendency for ICC to reduce velocity variation is associated with a safety benefit. On freeways, this benefit would be primarily in the velocity range between 88 and 112 km/h where ICC is mostly used. Fluctuations below this range are probably driven by congestion and fluctuations above this range, where traffic densities are most often low, are probably not an important collision risk factor.

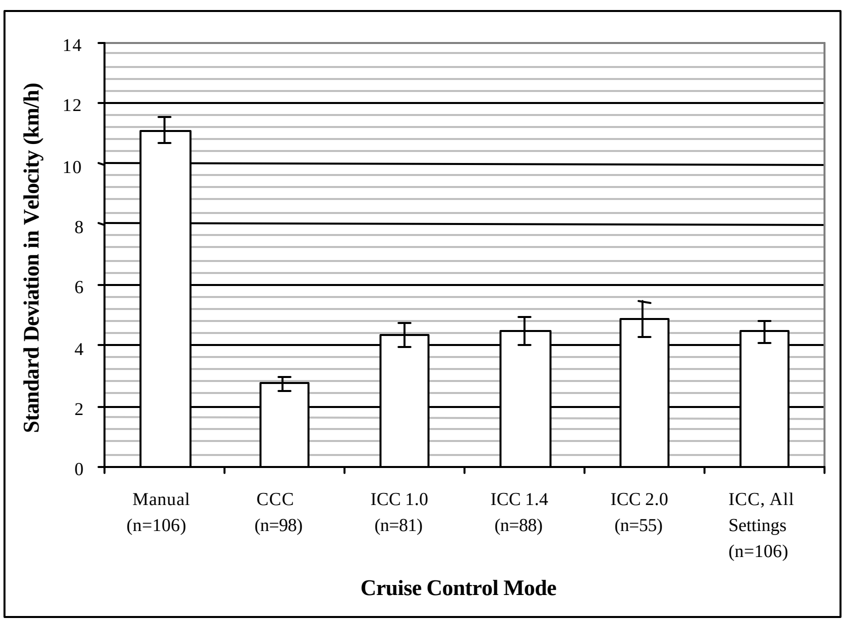

Figure 3-58 Standard Deviation in Velocity on Freeways as a Function of Cruise Mode

Thirty-nine drivers contributed standard deviations for all three ICC settings. There was no significant difference in velocity variability as a function of ICC setting. Therefore, the unweighted mean standard deviation across the three settings was computed. This unweighted mean is labeled "ICC, All Settings" in Figure 3-58. The mean standard deviations for Manual, CCC, and ICC (all settings) modes were submitted to an analysis of variance, with cruise mode as a repeated measure, and age group and previous cruise control use as between group measures. Data from 63 drivers were available for all three modes. There was no significant difference in velocity variability as a function of age group or previous cruise control use. Manual mode velocity variability was significantly greater than variability in ICC mode, and variability in ICC mode was significantly greater than variability in CCC mode. This is consistent with the following: 1) CCC is designed to operate at constant velocities, 2) ICC is designed to operate at constant velocities when there is no lead vehicle present and adjust to the lead vehicle velocity when it is less than the ICC set velocity, 3) the velocity under manual driving is continuously changing at the discretion of the driver, and 4) the manual mode is used more during heavy traffic and congestion. The overall effect of cruise mode was statistically reliable, $F(2, 92) = 711.7$, $p < 0.001$.

3.8.2.3 Velocity on Arterials. As can be seen in Figure 3-59, average velocity on arterials was lowest during manual driving. There was no difference between ICC and CCC and there was only very little difference amongst the headway settings with the lowest velocity occurring with the 2.0 second headway setting. All velocities were lower than their counterparts on freeways. The level of service data in Figure 3-25 suggest that this velocity pattern between modes would hold at each level of service but with slightly more equalization of the manual and ICC velocities at higher levels of service.

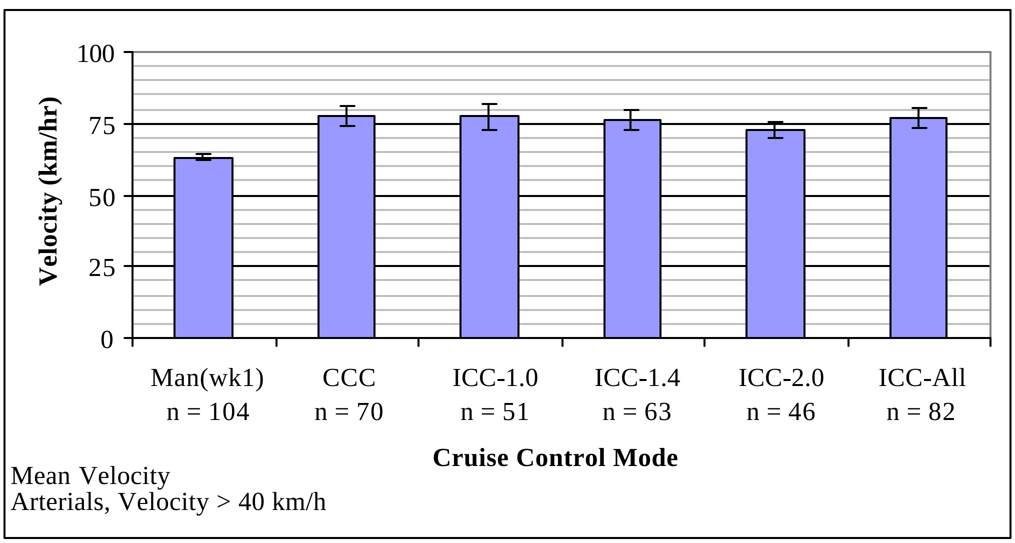

Figure 3-59 Velocity on Arterials as a Function of Cruise Control Mode and ICC Headway Setting

Figure 3-60 shows the velocity distributions for the three cruise modes. The CCC and ICC distributions were quite similar. With the cruise modes over 30 percent of the driving was less than 72 km/h as contrasted with manual driving which was over 68 percent. As might be expected virtually no driving with the cruise modes occurred below 56 km/h, the minimum set velocity (the cruise mode disengaged at 40 km/h).

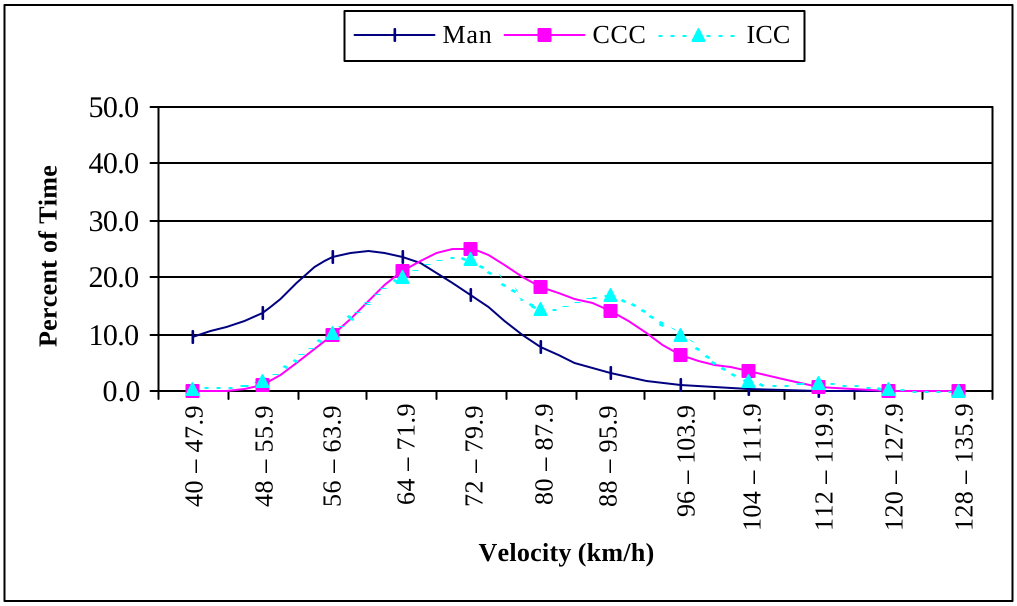

Figure 3-60 Percentage of Time on Arterials as a Function of Travel Velocity and Cruise Control Mode

Figure 3-61 shows the velocity distributions for the three headway settings on arterials. Drivers who used the 1.0 second setting tended to drive at higher velocities (greater than 104 km/h about 9 percent of the time) than drivers who used the other settings. Lower velocities (less than 72 km/h) were driven equally as much by drivers who used the 2.0 second setting as by drivers who used the 1.0 second setting (about 37 percent of the time).

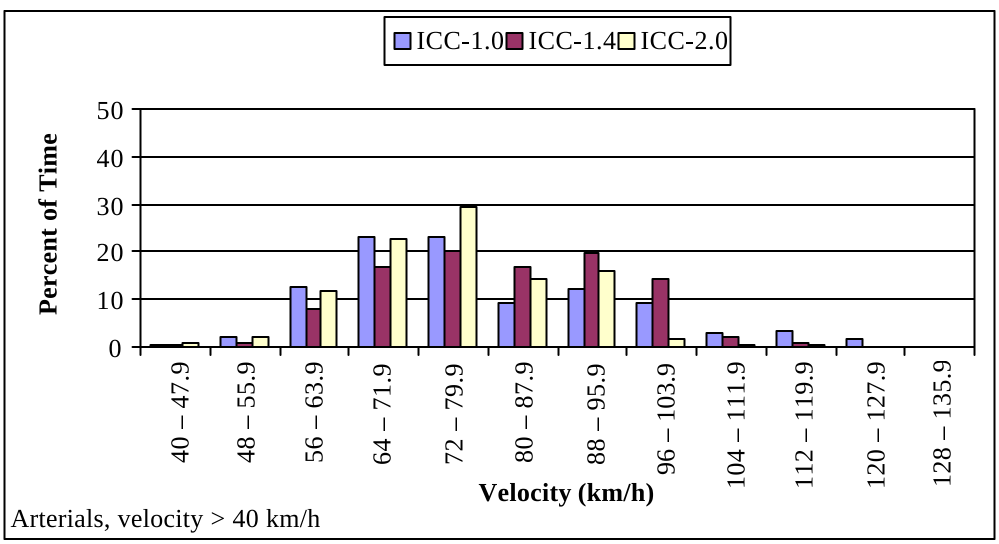

Figure 3-61. Percentage of Time on Arterials as a Function of Travel Velocity and ICC Headway Setting

3.8.2.4 Velocity Summary. On freeways, velocities with the cruise mode engaged were greater than the velocities during manual driving, and velocities with CCC were higher than with ICC. Very little driving was done below 80 km/h for any mode. The most likely explanation that much slower velocities and higher velocity variability was observed in manual driving relative to cruise control, is that drivers used CCC and ICC when congestion was light (levels of service A and B) and switched to manual control when they encountered traffic congestion. Another factor is that cruise control (CCC & ICC) functions in a manner to reduce speed variations compared to manual driving.

From a velocity perspective, including velocity variability, ICC appears to be neutral with respect to safety on freeways. Regardless of cruise mode, drivers gravitated towards a velocity between 104 and 112 km/h. The mean velocity of ICC tended to be intermediate between CCC and manual. Small differences in mean velocity between modes appear to have been the result of prevailing traffic conditions. There is no evidence in these data that suggest that drivers were influenced by the ICC system to drive faster.

Mean velocities on arterials were less compared to those on freeways. CCC and ICC velocities on arterials were about the same and greater than the velocities during manual driving. Almost no driving was done between 40 and 56 km/h with the cruise mode engaged. It appears that drivers chose to use cruise control on arterials only when traffic is light. From a velocity perspective, and similar to reasons given above for freeways, ICC appears to be neutral with respect to safety on arterials.

3.8.3 Acceleration and Acceleration Variability

3.8.3.1 Acceleration on Freeways. Accelerations and acceleration variations provide additional information on vehicle dynamics and potential safety effects. For the purpose of this analysis, it was assumed that higher accelerations, particularly high negative accelerations imply reduced safety. High decelerations in traffic are assumed to indicate an increased probability of rear end collisions because (a) following vehicles may need to decelerate at even higher rates to avoid collisions, or (b) the deceleration may often be associated with an attempt to avoid colliding with a preceding vehicle. High acceleration variability is associated with greater velocity variance between vehicles, and differences in velocity as mentioned earlier are associated with increased crash rates. Figure 3-62 shows the percent of time that the vehicles were in various acceleration modes. The data point on the abscissa labeled “0” represents the mean percent of time that the acceleration, in g force, was between –0.01 and 0.01. The point labeled 0.01 represents accelerations from 0.01 up to 0.05. Thus, except for the point labeled “0”, the labels indicate the lower bound for acceleration bins. It can be seen that CCC accelerations remained within a narrow band, as grade, wind, and road surface variation would have been the primary causes for fluctuation. ICC accelerations had a somewhat wider band of variation, as the vehicle would have adjusted velocity to accommodate preceding vehicles. Manual driving shows the widest range of variation as a result of braking and more aggressive driver throttle inputs.

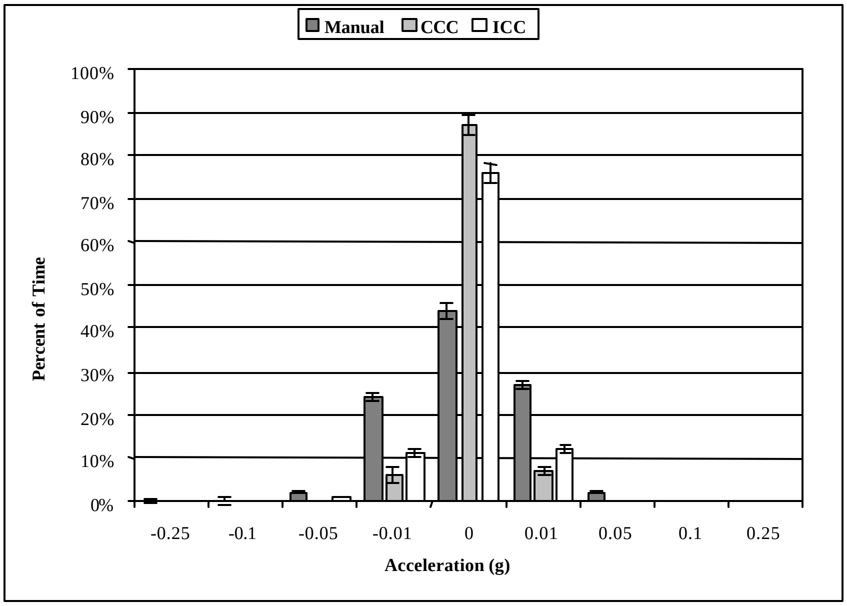

Figure 3-62 Distribution of Acceleration as a Function of Cruise Control Mode

3.8.3.2 Acceleration Variability on Freeways. Figure 3-63 shows the standard deviation of acceleration and may provide insight into the source of the large differences in velocity variability between manual control and cruise control modes. There is a clear trend of the variability to decrease with increasing velocity. At higher velocities fewer acceleration changes are made to maintain a desired velocity. The largest variability in acceleration was in velocities below 80 km/h in the manual mode. This indicates that the greatest source of variation in velocities for the manual mode occurs at lower velocities. This seems to be the reasonable result of drivers responding to the increased congestion and other traffic complexities that occur at lower velocities. Above this velocity, the variability in acceleration is still higher for manual control than for ICC or CCC, but the difference is smaller. The variability in acceleration for CCC is smallest, because CCC is designed to maintain a constant velocity.

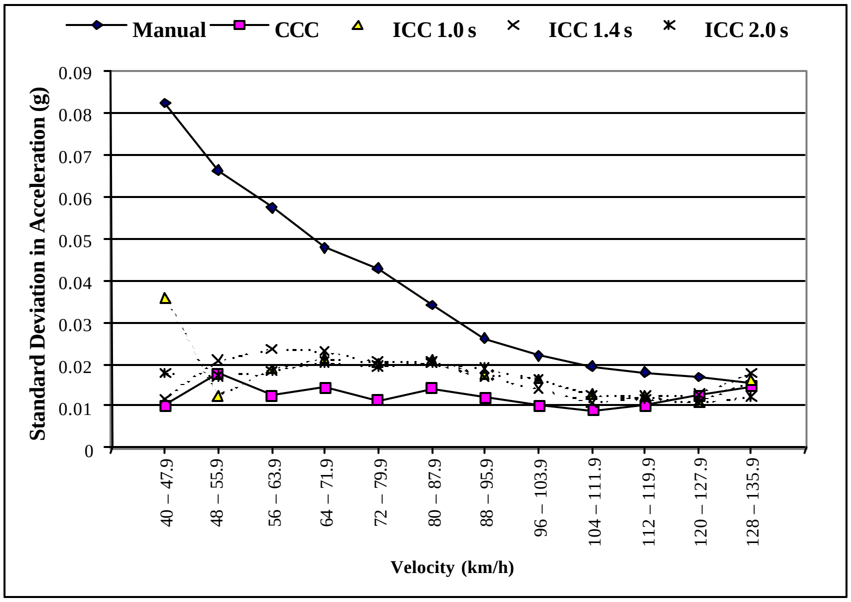

Figure 3-63 Standard Deviation in Acceleration as a Function of Velocity and Cruise Control Mode

3.8.3.3 Acceleration on Arterials. Figure 3-64 shows the percent of time that the vehicles were in various acceleration modes on arterials. Compared to freeways, accelerations on arterials had a slightly wider band for all cruise modes. As on freeways, CCC accelerations remained within a narrow band, ICC accelerations had an acceleration variation intermediate between CCC and manual. ICC accelerations between +0.01 g and +0.05 g, and between -0.01 g and -0.05 g doubled from 20 percent on freeways to 40 percent on arterials. Part of this may have been due to drivers resetting their velocity to accommodate roadway conditions.

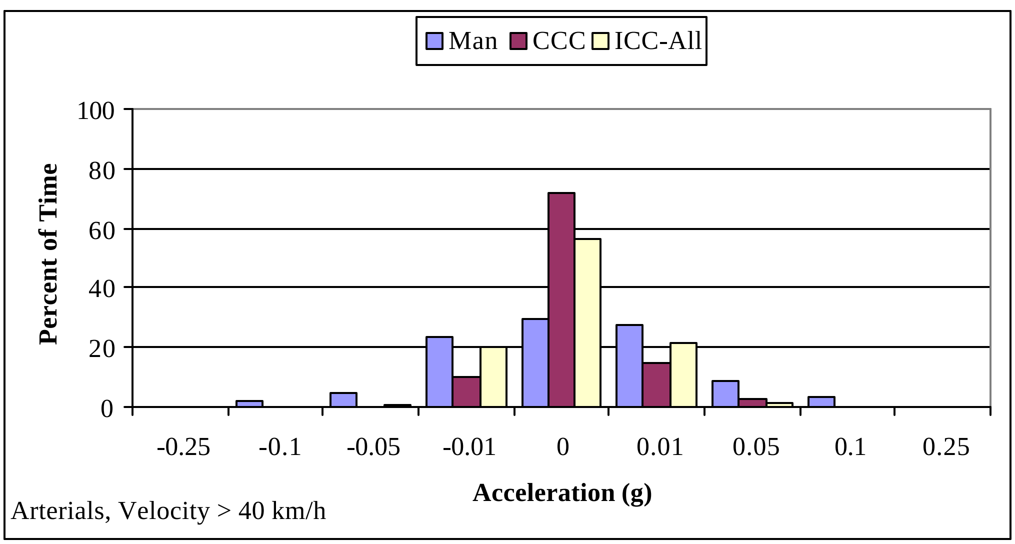

Figure 3-64 Distribution of Acceleration on Arterials as a Function of Cruise Control Mode

3.8.3.4 Acceleration Summary. CCC accelerations had a narrow band of variation and ICC accelerations had a somewhat wider band of variation. Manual driving showed the widest range of variation. For all cruise modes accelerations on arterials had a slightly wider band than accelerations freeways. There is a trend for acceleration variability to decrease with velocity. Overall, the tendency for ICC use to be associated with reduced acceleration variation compared to manual driving suggests a possible safety benefit.

3.8.4 Braking Frequency and Braking Force

3.8.4.1 Braking Frequency on Freeways. Pressing the brake pedal is a deliberate control action taken by the driver. It may be required or desired by the driver for the particular situation. Pressing the brake pedal also disengages the cruise control systems. In this analysis, a continuous braking event is associated with the cruise mode just prior to the braking. Any subsequent braking, even if immediately after disengaging the cruise system would be associated with the manual mode. Driving on freeways is examined in this section (disengagement on off-ramps would generally not be counted in this analysis). The brake force analysis was limited to initial velocities (velocities when brake was pressed) of 80 km/h or greater, and to the cases where a preceding vehicle was present. The goal of the latter two restrictions was to limit the analysis (particularly for manual driving) to less congested conditions under which most cruise control use occurred and to braking plausibly related to cruise control use (i.e., braking for preceding vehicles).

Figure 3-65 shows the frequency of brake presses per kilometer. It can be seen that brake applications occurred far more often in manual driving than in either cruise control mode. As intended, ICC appears to have relieved users of the need for some braking relative to CCC. The number of brake presses per kilometer was reduced from 0.25 for manual driving to 0.05 for ICC driving - a factor of five. The reductions from CCC driving (0.12 brake presses per kilometer) was also substantial. Further, it can be seen that braking frequency is negatively related to headway setting, an intuitively understandable relationship, i.e., as distance to a decelerating preceding vehicle declines because of shorter headway selections, the real or perceived need for driver brake intervention becomes greater. A separate examination of brake presses during periods of congestion, i.e., between 40 and 80 km/h, indicated that the rates increased by a factor of 7 for manual driving, a factor of 5 for CCC, and a factor of 10 for ICC. Even though the differences between modes are less the relative results are consistent with braking frequency above 80 km/h.

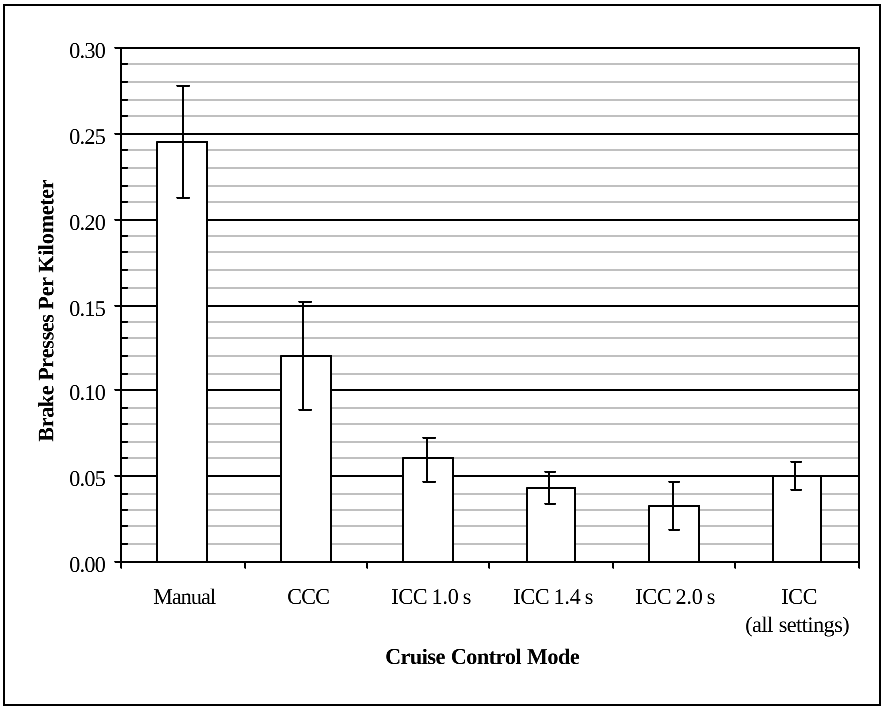

Figure 3-65 Mean Number of Brake Presses per km on Freeways as a Function of Cruise Control Mode (N = 100)

There were 63 drivers from whom brake press data were available for all three cruise modes (manual, CCC, ICC). The data for these drivers was submitted to analysis of variance. The main effect of cruise mode was significant, F (2, 188) = 54.4, $p < 0.001$. There was also a cruise mode by previous cruise use interaction, F (2, 188) = 4.7, $p <$ 0.05. This rather complex interaction can be seen in Figure 3-66 where cruise control users have about the same number of brake presses as nonusers in manual mode, many fewer brake presses in CCC mode, and again about the same number of brake presses in ICC mode. The lack of difference between nonusers and users in the ICC mode may be an indication that nonusers soon become equally adept regarding the circumstances under which disengagement of the ICC is warranted.

Figures 3-65 and 3-66 show that both ICC and CCC use are associated with significantly and substantially lower braking rates than manual control. This correlates with the findings on lane changes and cut-ins. Namely, both ICC and CCC use are associated with significantly and substantially lower lane change and cut-in rates compared to manual control. Figure 3-65 also shows that ICC reduced the number of brake presses per kilometer driven in the mode by 58 percent relative to CCC. This occurred without any reduction in lane change or cut-in rate, indicating that the drivers allowed the ICC system to effectively adjust the velocity to that of the preceding vehicle. Any reductions of brakings associated with large decelerations would suggest a safety benefit.

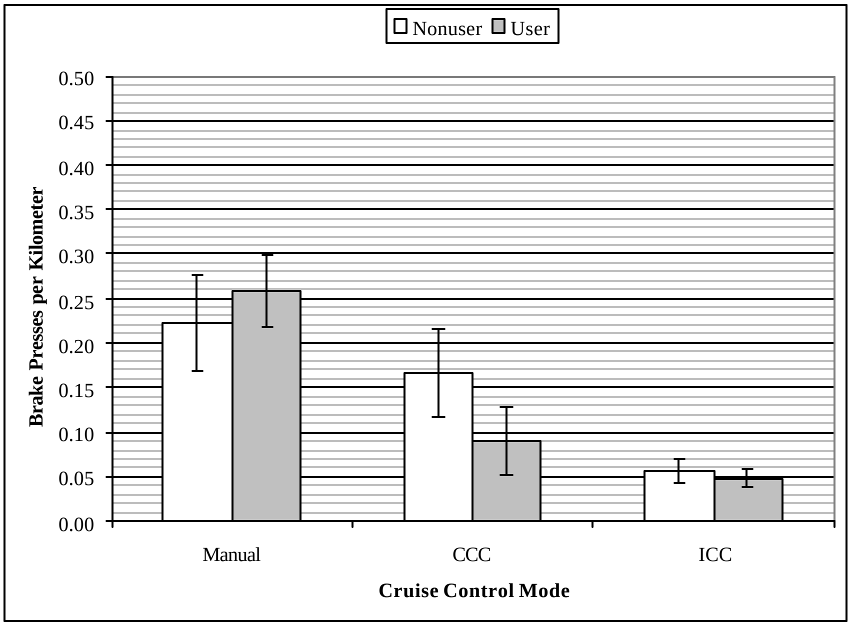

Figure 3-66 Brake Presses per Kilometer as a Function of Cruise Control Mode and Prior Cruise Control Experience

3.8.4.2 Braking Force on Freeways. Figure 3-67 shows a histogram of maximum deceleration (minimum negative acceleration) associated with each brake press on the freeway where there was a preceding vehicle present and the velocity at the time of the brake press was greater than 80 km/h. The abscissa label represents the minimum deceleration value for that interval, thus the interval labeled –0.25 g represents all maximum decelerations in the interval from – 0.25 g to – 0.30 g. Table 3-39 shows the actual numerical values.

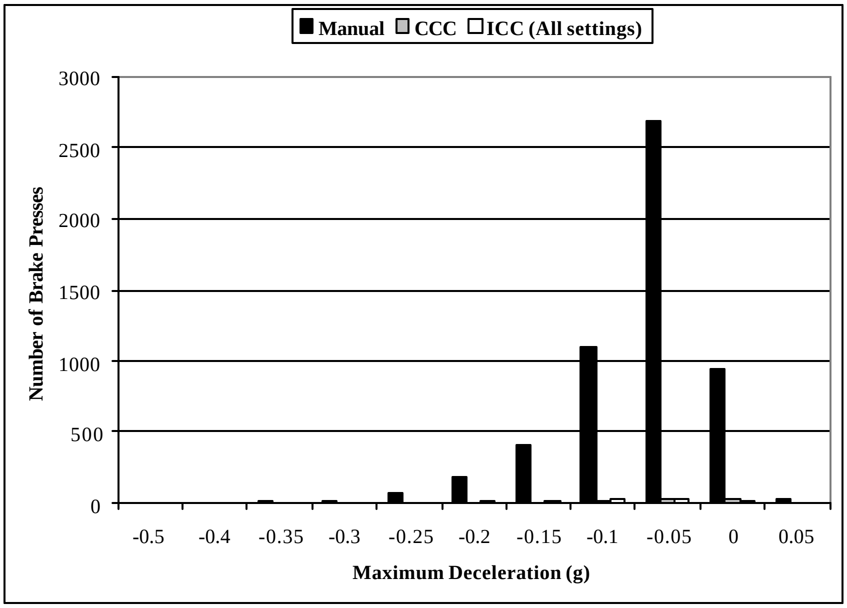

Figure 3-67 Number of Brake Presses Categorized by Maximum Deceleration Associated with Each Brake Press and Cruise Control Mode

Table 3-39 Numerical Values Number of Brake Presses Categorized by Maximum Deceleration Associated with Each Brake Press and Cruise Control Mode

	-0.5	-0.4	-0.35	-0.3	-0.25	-0.2	-0.15	-0.1	-0.05	0	0.05
Manual	2	2	5	20	79	188	406	1089	2680	950	28
CCC	0	0	0	0	0	0	1	11	29	22	0
ICC (All settings)	0	0	0	1	2	5	13	23	30	19	2

Because the vast majority of brake presses occurred in manual driving, Figure 3-68 and Figure 3-69 show manual and cruise control separately, and plot maximum deceleration as a function of million of vehicle kilometers traveled. Figures 3-68 and 3-69 show that, with the possible exception of extremely rare brakings greater than 0.25g, ICC or CCC use results in significantly less forceful brakings than manual driving. As mentioned above, this reduction suggests a safety benefit. Table 3-40 and 3-41 show the numerical values corresponding to Figures 3-68 and 3-69 respectively.

It is interesting to note that the braking results presented in Figure 3-69 provide strong evidence that the time-headway and velocity control features of the ICC system relieve drivers of the need for some braking interventions relative to CCC. In the deceleration range of 0 g to -0.1 g, which includes the deceleration control authority of the ICC system (about 0 g to -0.07 g), the braking rate of ICC drivers is about half that of CCC drivers.

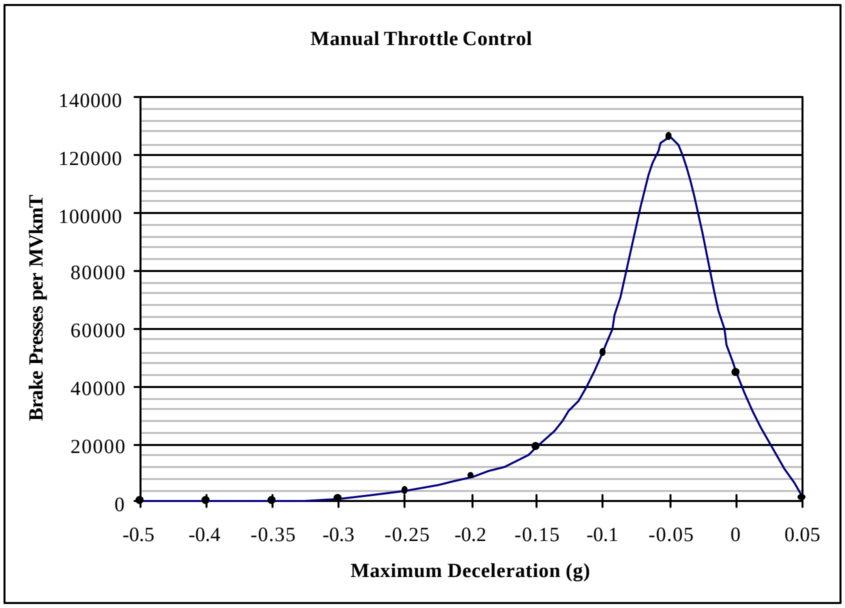

Figure 3-68 Brake Press per Million Vehicle Kilometers Traveled in Manual Mode on Freeways when Velocity was Greater Than 80.5 km/h, and Lead Vehicle was Present

Table 3-40 Numerical Values Number of Brake Press per Million Vehicle Kilometers Traveled in Manual Mode on Freeways when Velocity was Greater Than 80.5 km/h, and Lead Vehicle was Present

	-0.5	**-0.4**	**-0.35**	**-0.3**	**-0.25**	**-0.2**	**-0.15**	**-0.1**	**-0.05**	**0**	**0.05**
Manual	94	94	235	940	3715	8841	19092	51210	126026	44674	1317

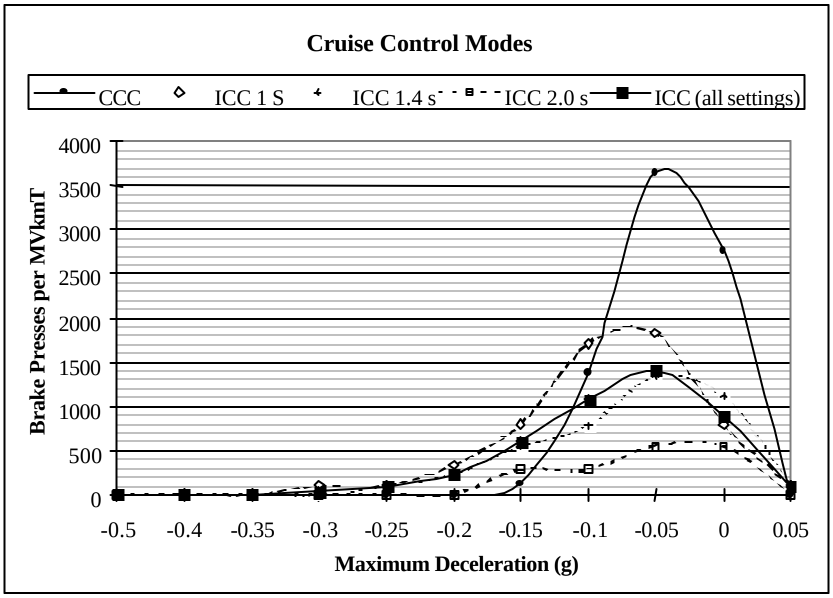

Figure 3-69 Brake Press per Million Vehicle Kilometers Traveled in CCC and ICC Modes on Freeways When Velocity was Greater Than 80.5 km/h, and Lead Vehicle was Present

Table 3-41 Numerical Values Number of Brake Press per Million Vehicle Kilometers Traveled in CCC and ICC Modes on Freeways When Velocity was Greater Than 80.5 km/h, and Lead Vehicle was Present

	-0.5	-0.4	-0.35	-0.3	-0.25	-0.2	-0.15	-0.1	-0.05	0	0.05
CCC	0	0	0	0	0	0	126	1383	3646	2766	0
ICC 1.0s	0	0	0	114	114	342	799	1712	1826	799	114
ICC 1.4s	0	0	0	0	111	222	554	776	1330	1109	111
ICC 2.0s	0	0	0	0	0	0	275	275	550	550	0
ICC (All Settings)	0	0	0	47	93	233	606	1072	1398	885	93

Figure 3-70 shows the proportion of brake presses in each cruise mode that fell into each of the maximum deceleration categories. Table 3-42 shows the numerical values. It can be seen in Figure 3-70 that with ICC there is a shift to the left in the distribution of maximum deceleration, that is, proportionately there are slightly more severe decelerations with ICC relative to either manual braking or CCC. (Note that the actual frequency of severe deceleration for ICC is generally less than manual.) However, even the most severe brakings in these distributions are substantially less than -0.7 g which is generally considered to be maximum deceleration on dry pavement.

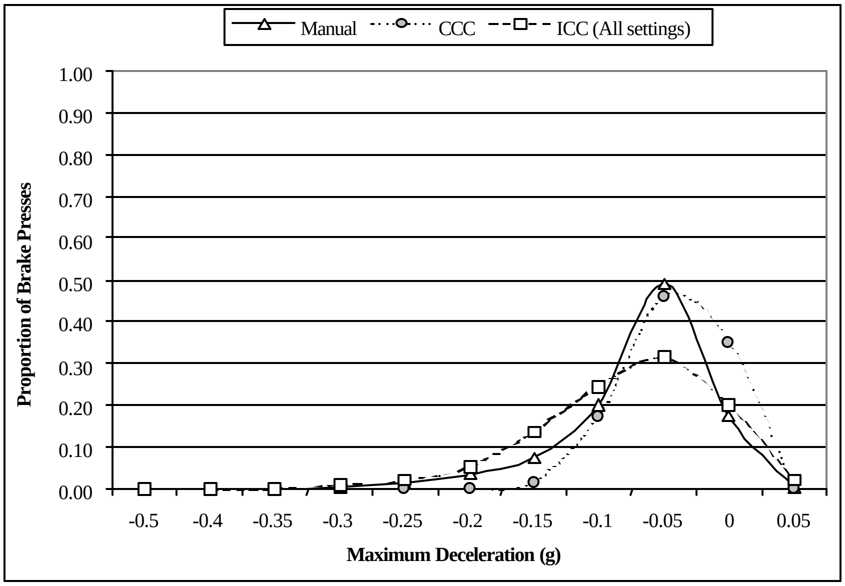

Figure 3-70 Proportion of Brake Presses as a Function of Maximum Deceleration and Cruise Control Mode

Table 3-42 Numerical Values Proportion of Brake Presses as a Function of Maximum Deceleration and Cruise Control Mode

	-0.5	**-0.4**	**-0.35**	**-0.3**	**-0.25**	**-0.2**	**-0.15**	**-0.1**	**-0.05**	**0**	**0.05**
Manual	0.000	0.000	0.001	0.004	0.014	0.035	0.075	0.200	0.492	0.174	0.005
CCC	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.175	0.460	0.349	0.000
ICC (All settings)	0.000	0.000	0.000	0.011	0.021	0.053	0.137	0.242	0.316	0.200	0.021

3.8.4.3 Braking Frequency on Arterials. The brake force analysis was limited to initial velocities (velocities when brake was pressed) of 56 km/h or greater, and to the cases where a preceding vehicle was present. Figure 3-71 shows the frequency of brake presses per kilometer on arterials. As might be expected, the rates on arterials were substantially higher than those on freeways. However, the main trends were similar to those for freeways. Namely, brake applications occurred far more often in manual driving than in either cruise control mode. ICC appears to have relieved users of the need for some braking relative to CCC. One main difference between freeways and arterials was the relationship between brake frequency and ICC headway setting. On freeways, there was an inverse relationship. This appeared to be intuitive: closer headways meant more perceived danger resulting in more brakings. On arterials, there was no statistical difference, but a slight tendency towards a direct relationship can be seen. The relationship may be explained by the more cautious nature of the 2.0 second headway setting drivers who tended to fall into the older age group. On freeways this age group may have had fewer interactions with a lead vehicle. Or it may be that on arterials, roadway factors, i.e., intersections, curves, etc., tend to neutralize the effects of the headway setting.

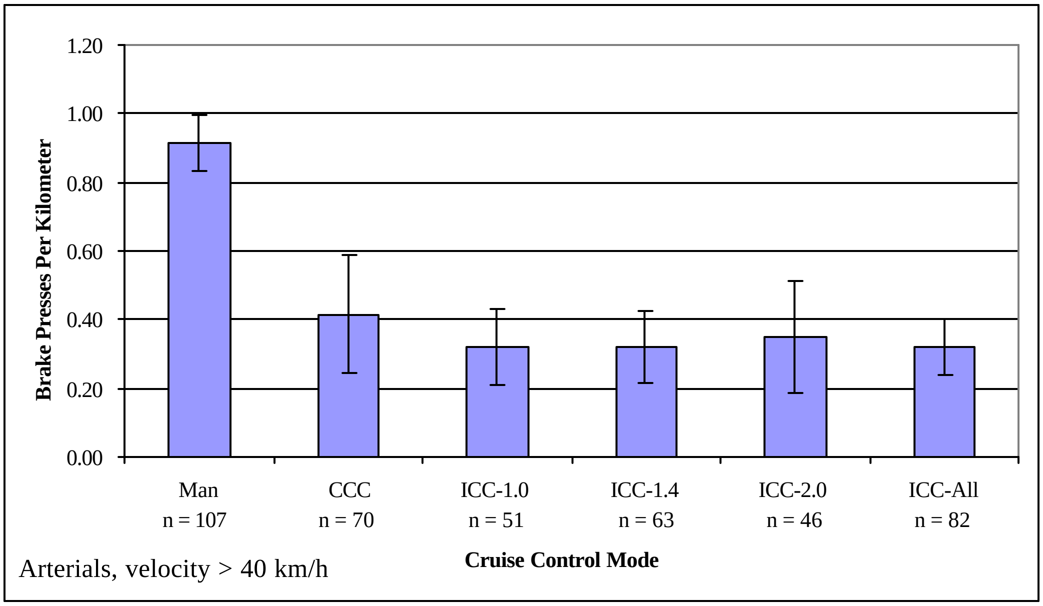

Figure 3-71 Mean Number of Brake Presses per km on Arterials as a Function of Cruise Control Mode

3.8.4.4 Braking Force on Arterials. Figure 3-72 shows a histogram of maximum deceleration (minimum negative acceleration) associated with each brake press on arterials where there was a preceding vehicle present and the velocity at the time of the brake press was greater than 56 km/h. Table 3-43 shows the numerical values. Once again, the vast majority of brake presses occurred in manual driving. Furthermore, substantially more brake presses involving maximum decelerations greater than 0.15 g occurred on arterials.

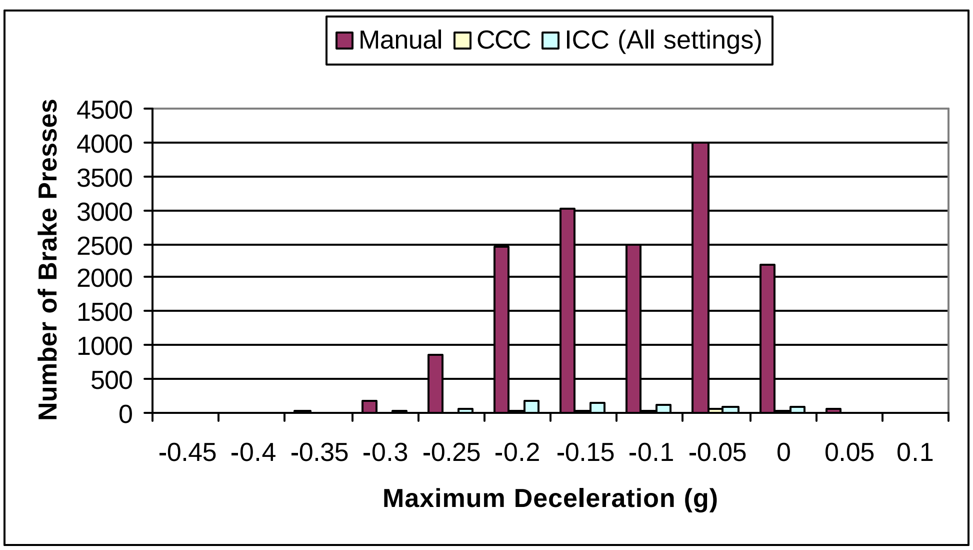

Figure 3-72 Number of Brake Presses Categorized by Maximum Deceleration Associated with Each Brake Press and Cruise Control Mode

Table 3-43 Numerical Values Number of Brake Presses Categorized by Maximum Deceleration Associated with Each Brake Press and Cruise Control Mode

	-0.45	-0.4	-0.35	-0.3	-0.25	-0.2	-0.15	-0.1	-0.05	0	0.05	0.1
Manual	2	1	25	185	855	2457	3027	2473	3986	2185	50	2
CCC	0	0	0	1	8	21	24	43	51	35	2	0
ICC (All settings)	0	2	10	27	70	168	159	130	98	78	0	0

Figure 3-73 shows the proportion of brake presses in each cruise mode that fell into each of the maximum deceleration categories. Table 3-44 shows the numerical values. It can be seen in Figure 3-73 that as was the case on freeways, with ICC there is a shift to the left in the distribution of maximum deceleration. Over 15 percent of the brake presses in the ICC mode are greater than 0.25g. This compares to about 7 percent for CCC and manual. It should be mentioned that even though the proportion is higher for ICC, in absolute numbers it is extremely rare and less than manual. It is also of interest to note from Figure 3-73 that, as with freeway driving, the proportion of ICC braking in the 0.0 to 0.1g interval is significantly less than for CCC and manual, indicating that ICC control is relieving drivers of the need for some braking interventions in this interval.

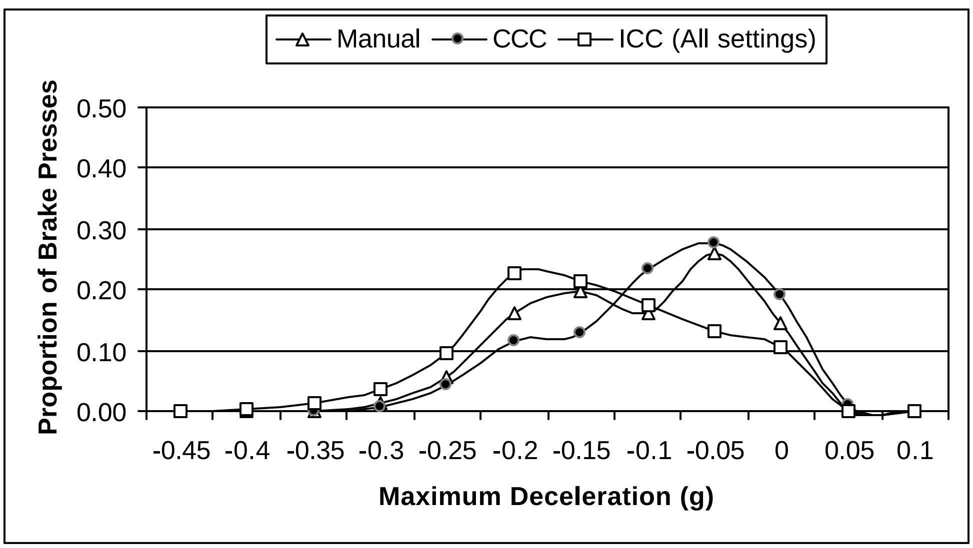

Figure 3-73 Proportion of Brake Presses as a Function of Maximum Deceleration and Cruise Control Mode

Table 3-44 Numerical Values Proportion of Brake Presses as a Function of Maximum Deceleration and Cruise Control Mode

	-0.45	-0.40	-0.35	-0.30	-0.25	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10
Manual	0.0001	0.000	0.002	0.012	0.056	0.161	0.199	0.162	0.261	0.143	0.003	0.000
CCC	0.0000	0.000	0.000	0.005	0.043	0.114	0.130	0.232	0.276	0.189	0.011	0.000
ICC (All settings)	0.0000	0.003	0.013	0.036	0.094	0.226	0.214	0.175	0.132	0.105	0.000	0.000

3.8.4.5 Braking Summary. These results appear to show that participants used the ICC system as intended: to reduce the amount of braking intervention required when cruise control is used. In this sense, the fewer brakings for ICC is considered a safety benefit.

To achieve this benefit, ICC users had to delay tapping the brake pedal, relative to when they would have tapped the brake in either manual or CCC. However, given that they delayed pressing the brake, if it later became evident that the vehicle would not maintain a comfortable gap on its own, a higher braking force would be required to achieve the desired gap. Given that very few cases of deceleration greater than - 0.25 g were observed with ICC, it appears that the drivers were monitoring headway carefully. Futhermore, there were less forceful brakings per million vehicle kilometers traveled with ICC compared to manual driving, suggesting a safety benefit. A detailed analysis of selected cases of severe braking events is presented in Section 3.9.2.3

3.8.5 Response Time

3.8.5.1 Methodology. To explore whether ICC might influence drivers' response time to highway stimuli, especially to critical stimuli requiring immediate response, the video analysis tool described in Appendices H and I was used to measure response times. Four categories of stimuli and three categories of response were available to the analyst as part of the tool's user interface. In addition, an 'other' category was available for classifying stimuli and responses in special cases.

The video analyst was encouraged to record response times whenever stimuli and responses could be identified. This report focuses on the video episodes that could be unambiguously classified. The criteria used to identify response times appropriate for analysis were:

1. Road class could be verified using the GIS database.
2. The analyst judged that both the stimulus and response onset times were concisely measurable from the video.
3. The analyst was confident that there was a need for a response to the identified stimulus, i.e., either braking or steering were required.

Because drivers can anticipate situations that may require braking, and because drivers might have attended to stimuli that were not visible in the video, there was no way to be certain that the stimulus that the analyst recorded was the stimulus that caused the driver to act. Thus, this analysis relied on the analyst's rating, on a three-point scale, of confidence that the stimulus-response pair was appropriate. Only stimulus-response pairs given the highest confidence rating by the analyst are reported. Even with this high confidence rating, care needs to be given to the interpretations of the response times. In the opinion of the evaluators, the time response should be viewed on face value. They are time differences between designated stimuli and designated responses that occurred in an operational environment.

3.8.5.2 Response Time on Freeways. Table 3-45 shows the total number of response times recorded by the analyst for freeway driving.

Table 3-45 Response Time Data - Freeways

Stimulus	***Response***		
	Brake-Pedal	**Foot-off-Gas**	**Lateral Maneuver**
Brake-Light	545	151	3
Deceleration - No Brake	6	5	0
Obstacle	1	1	0
Cut - In	22	12	0

Only the brake-light stimulus to brake-pedal response category provided a sufficient number of samples to warrant further analysis.

In the brake-light-stimulus to brake-pedal-response category, there were 34 drivers for whom response times were recorded in both manual and ICC modes on freeways. There were not enough response times in the CCC mode to enable meaningful comparisons with other modes. The mean response times for these 34 drivers are shown in Figure 3-74. Response times were significantly longer in ICC compared to manual, F (1, 28) = 7.3, $p < 0.05$. Among the 20 to 30 and the 60 to 70 age groups, ICC latencies were about a half-second longer than they were in the manual mode. This difference was not evident among the middle-aged group, hence a significant age- group-by-mode interaction, F (2, 28) = 4.8, $p < 0.05$. Although the older age group had longer average response times, the age group main effect was not statistically reliable.

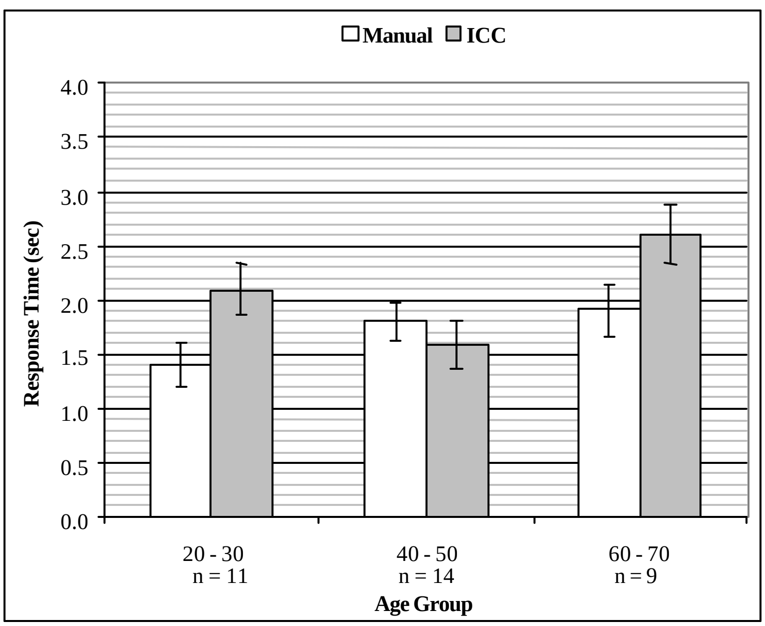

Figure 3-74 Average Response Time on Freeways by Age Group and Cruise Control Mode

To be included in the above analysis, each driver had to have at least one response time in manual mode and one response time in ICC mode. This enabled each driver to serve as his own control. There were 67 drivers with at least one brake-light to brake-pedal response time in manual, and 40 drivers with a least one response time in ICC, and 19 with at least one response time in CCC. Means based on all available brake-light to brake-pedal responses are shown in Figure 3-75. For the entire sample, the mean difference between manual and ICC response times on freeways is not statistically reliable, $p > 0.07$. The CCC response time mean was reliably different from the manual response time, but not different from the ICC response time.

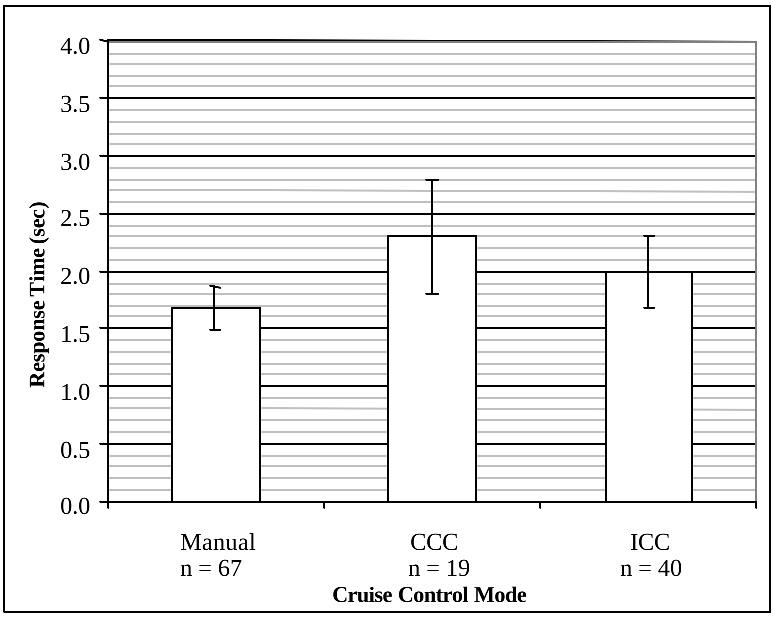

Figure 3-75 Brake-Light Stimulus to Brake-Pedal Response Time for Entire Sample - Freeways

The pattern that emerges from the analysis of response times, estimated to the nearest 1/10th second from the video analysis tool, suggests that drivers using cruise control wait longer to respond after the brake lights of the preceding vehicle come on. That the delays are similar whether ICC or CCC is in use suggests that this phenomenon is not unique to ICC systems.

Previously it was shown that time-headway varies as a function of cruise control mode, and that CCC and ICC yield longer average time-headways than manual driving. Longer time-headways would allow longer delays before braking is required. To investigate this hypothesis, the 531 response times for which time-headway was available are plotted in Figure 3-76 as a function of time-headway. It can be seen from the figure that the data points show a weak correlation between increased time-headway and increased response time.

It can also be seen from the figure that there were a number of occurrences of short time-headways and short response times. Most of these were for manual driving as the driver kept a very short headway and anticipated braking of the lead vehicle. There were a few instances of ICC driving also with short time-headways and short response times. The short time-headways come about during dynamic interactions with the other vehicle. The combination of long response times and short time-headways generally involved situations where the lead vehicle either decelerated very mildly or braked for very short periods.

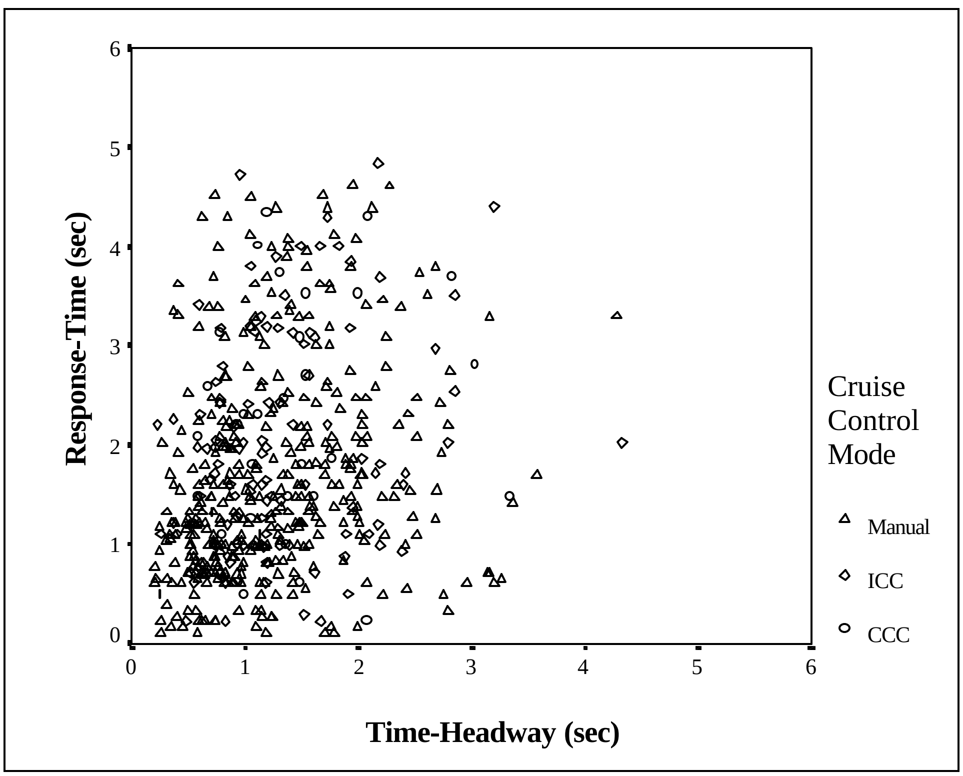

Figure 3-76 Brake-Light Stimulus to Brake-Pedal Response Time on Freeways Plotted as a Function of Time-Headway

There was a small correlation between time-headway and response time, r = .24, that accounted for 5.6 percent of the variance in response time. A multiple regression with response time as the dependent measure and driver, cruise mode, and time-headway as predictors yielded an R^2 of 0.28, $F(75, 455) = 2.34$, $p < 0.001$. In this analysis, driver was forced to enter the regression first, and accounted for 23.9 percent of the variance in response time. Cruise mode was forced into the regression second, and accounted for a statistically non-significant 0.6 percent of the variance. Entered at the last step of the regression, time-headway accounted for 3.3 percent of the variance, and was a reliable predictor of response time, $F(1, 455) = 20.64$, $p < 0.001$. Thus it is reasonable to hypothesize that, on freeways, the slight increase in driver response times for ICC and CCC are due in part to ICC and CCC being associated with longer time-headways and drivers using the longer headway to delay their responses to slower vehicles. A further examination of these data, with distinctions between the modes, is provided in Section 3.9.1.5.

3.8.5.3 Response Time on Arterials. Table 3-46 shows the total number of response times the analyst recorded for arterial driving.

Table 3-46 Response Time Breakdown - Arterials

Stimulus	***Response***		
	Brake-Pedal	**Foot-off-Gas**	**Lateral Maneuver**
Brake-Light	345	105	0
Deceleration - No Brake	9	7	0
Obstacle	0	0	0
Cut – In	6	4	0

Figure 3-77 shows the mean response times on arterials by mode. As can be seen, the ICC response time was not reliably different from the manual response time.

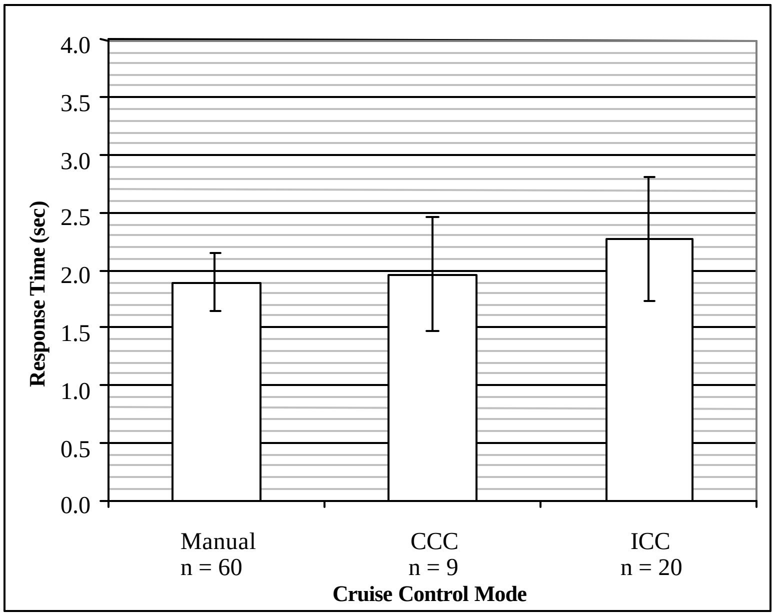

Figure 3-77 Brake-Light Stimulus to Brake-Pedal Response Time for Entire Sample - Arterials

Brake-pedal responses to brake-light stimuli results on arterials are shown in Figure 3-78 as a function of time-headway. Because of the slower velocities, the ICC system was able to record longer headways.[3] A result of the greater time-headways measured on arterials was that the correlation between response time and time-headway is somewhat higher than for freeways, r = 0.30. As for freeways, linear regression was performed in which driver, cruise mode, and time-headway were entered in respective order. Driver accounted for 26.3 percent of the variance in response time. Mode was not a significant predictor of response time, and accounted for .07 percent of the variance. After accounting for individual differences and mode, time headway was still a strong predictor of response time, $F(1, 255) = 21.4$, $p < 0.001$. Thus individual driving styles and time-headways account for most of the response time differences observed on arterials. Response times are further examined in Section 3.9.1.5 by the criticality of the event precipitating the response including close headways high levels of lead vehicle deceleration and large velocity reductions.

[3] The sensor is limited by distance, not time, and therefore it can record longer time gaps at lower velocities. See Section 3.8.1.2 for further discussion on time headways at lower velocities.

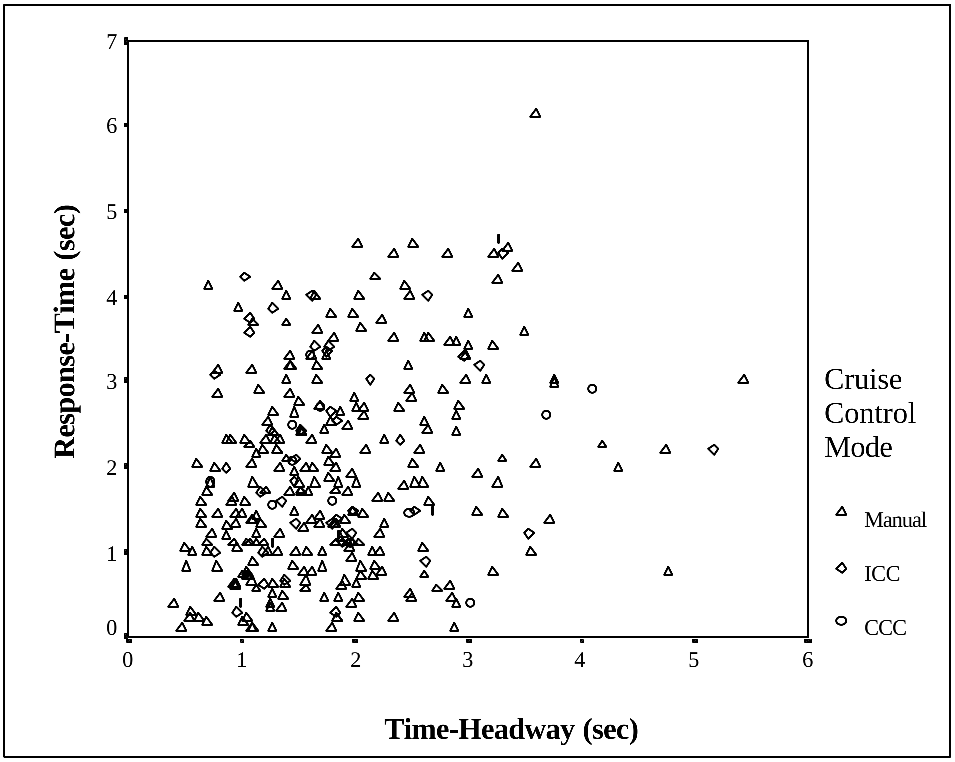

Figure 3-78 Brake-Light Stimulus to Brake-Pedal Response Time on Arterials Plotted as a Function of Time-Headway

3.8.5.4 Response Time Summary. In summary, the response time data are consistent with ICC being associated with longer time-headways, and drivers using the longer headways to delay their responses to slower vehicles. These results are also consistent with observations discussed later in Section 3.9.2.2 that ICC drivers tend to wait for the ICC system to respond to a situation so as to avoid ICC disengagement. Whereas the slightly longer response times for ICC may initially appear to suggest a safety disbenefit, several factors should be considered: (1) the longer response times do not appear to be due to inattentiveness since evidence from the driver questionnaires suggests that ICC drivers are well aware of closing events, and (2) results of the braking analysis and critical scenario analysis suggest that only in extremely rare situations do drivers wait so long that severe braking is required. The response time measure is therefore viewed as a safety concern, but not an indication of a general safety problem with the ICC system. Further analysis of response time is performed in Section 3.9.1.5 as a function of criticality of the event precipitating the response.

3.9 Behavior in Safety-Critical Situations

In this section the safety performance measures are presented to determine how drivers performed in safety-critical driving situations. The safety-critical driving situations that are examined here are closings and pre-crash scenarios.

3.9.1 Driving Behavior During Closing States

It is to be noted that driving exposure during closing states on arterials was extremely low amounting to a total of only 16 hours or 4% of the total driving on arterials greater than 40 km/h. Further, the average participant used ICC on arterials for only 10.5 minutes and twenty-one drivers never used ICC on arterials. Freeway results are therefore emphasized in this section. Where results are presented for both roadway types, greater confidence is placed on the freeway results. The closing rate measure, which tends to characterize this safety critical driving situation, is presented first.

3.9.1.1 Closing Rate

3.9.1.1.1 Closing Rate on Freeways. Figure 3-79 shows mean closing rates between the lead vehicle and the host vehicle on freeways when the velocity was greater than 80 km/h. The mean was taken only when a lead vehicle was present and there was a closing condition. As can be seen in the figure, mean closing rates on freeways was lowest for ICC and highest for CCC. It is interesting to contrast these results with the percent of time spent in closing states, as shown in Table 3-6, where ICC and CCC were about the same and lower compared to manual. Apparently, when in a closing state, CCC drivers tolerated higher closing rates than either manual or ICC. The minimal difference between manual and ICC probably indicates that the ICC system is controlling headways and closings much as a driver does. It may be further noted that the highest closing rate for CCC is consistent with its inability to adjust velocities to a leading vehicle, unlike ICC and manual; hence, it is expected that, on average, its constant velocity feature would result in greater closing rates.

There was no significant difference between the manual and ICC modes. Closing rates were inversely proportional to the headway setting. This may be partially explained by the more cautious nature of the 2.0 second headway setting drivers who tended to fall into the older group category. Furthermore, the closing rate results for the different ICC headway settings and manual are consistent with closing state results in Tables 3-7 and 3-10. Specifically, as ICC headway settings increase the closing rates and percent of time in closing states decreases. This is expected as longer headways will allow more time for the ICC system to adjust velocities to match the lead vehicle and thus reduce average closing rates. Also, note that the 1.0 second ICC headway setting and manual driving both have similar closing rates and distributions of time in the closing sub-states.

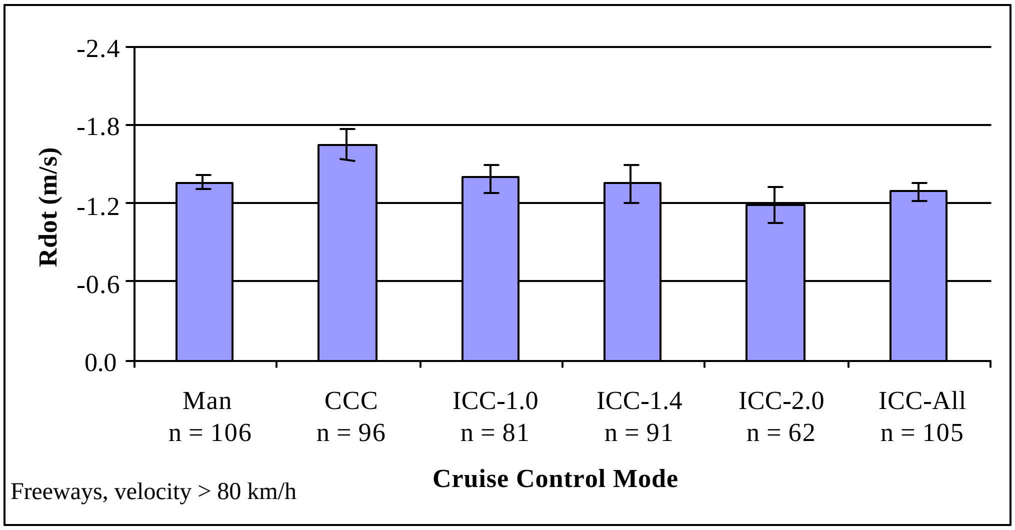

Figure 3-79 Mean Closing Rate on Freeways as a Function of Cruise Control Mode and ICC Headway Setting

Figure 3-80 shows the closing rate distribution in comparison to the separating rate distribution. These distributions exclude those cases where no vehicle is present and cases where Rdot = 0. It can be seen from the figure that CCC has more higher closing rates and overall about 80 % of the closing rates are between 0 and 3 m/s. The closing rates are about equally balanced with the separating rates.

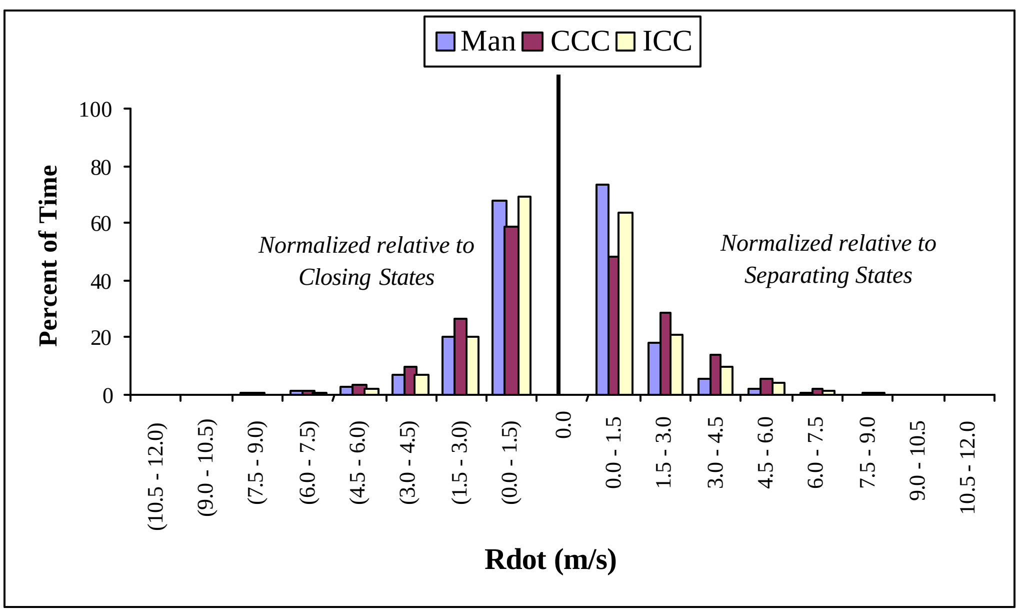

Figure 3-80 Closing Rate Distribution Versus Separating Rate Distribution – Excluding Rdot = 0

Figure 3-81 shows the mean closing rates as a function of level of service. There is a distinct reduction in mean closing rates as the level of congestion increases probably because more traffic forces drivers to drive at similar velocities.

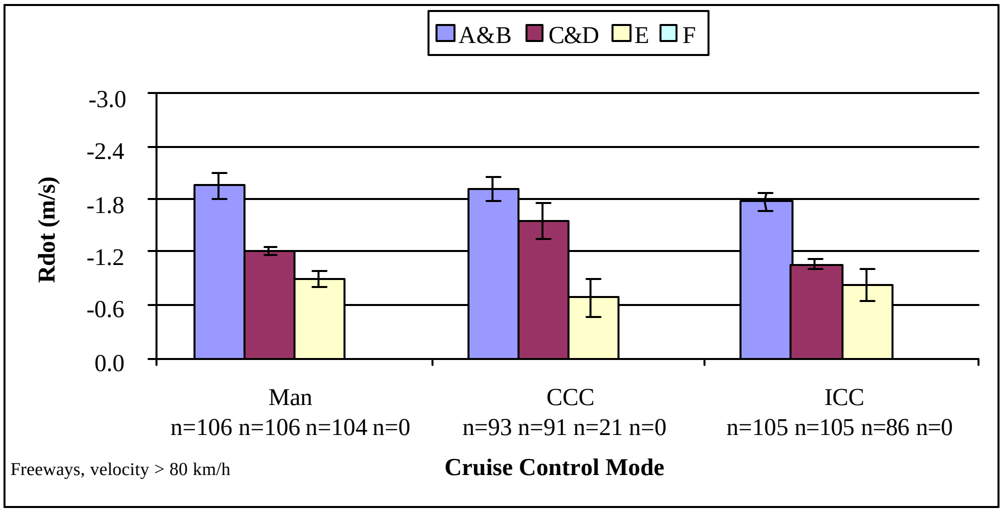

Figure 3-81 Mean Closing Rate as a Function of Cruise Control Mode and Level of Service

3.9.1.1.2 Closing Rate on Arterials. Figure 3-82 shows mean closing rates between the lead vehicle and the host vehicle on arterials when the velocity was greater than 56 km/h. From previous usage results on arterials, cruise modes, either ICC or CCC, were seldom used at velocities below 56 km/h, and other than in light traffic conditions (level of service A&B). It can be seen from the figure that closing rates on arterials were substantially higher than those on freeways. CCC once again had the highest closing rates. The closing rates for ICC were slightly greater than those for manual. The manual closing rates and the ICC closing rates with a headway setting of 2.0 seconds were significantly different. There was a significant reversal in the trend regarding headway setting. On arterials, mean closing rates increased with headway setting.

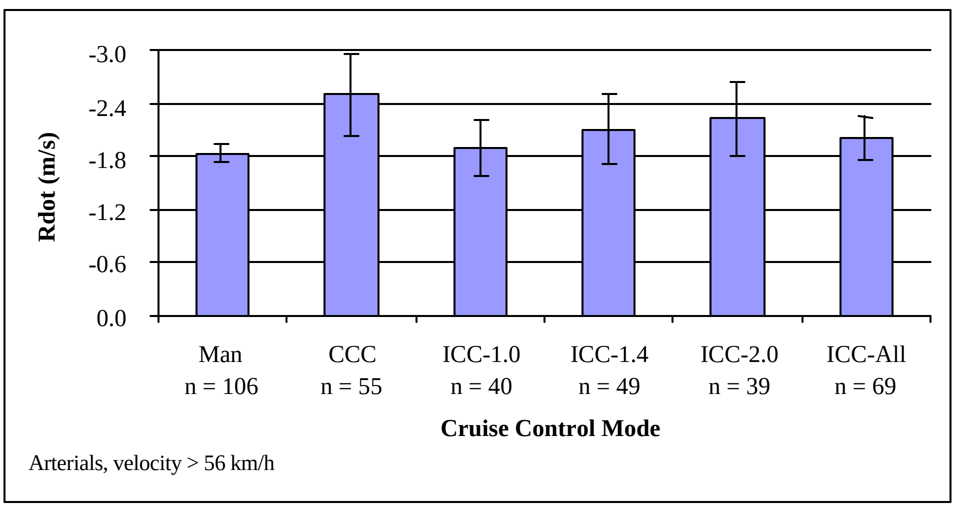

Figure 3-82 Mean Closing Rate on Arterials as a Function of Cruise Control Mode and ICC Headway Setting during Closings

3.9.1.1.3 Closing Rate Summary. On freeways above 80 km/h, where most of the driving was done, including that for manual driving, closing rates were highest for CCC and lowest for ICC. There was very little difference in closing rates between ICC and manual. Closing rates were inversely proportional to ICC headway setting.

On arterials above 56 km/h, closing rates were again highest for CCC but now lowest for manual. In contrast to freeway driving, closing rates were proportional to ICC headway setting. Most of the driving on arterials, including that for manual driving, was above 56 km/h and during periods of light traffic.

There is thus some evidence on freeways and arterials that ICC reduces the level of closing rates compared to CCC. In manual driving, drivers had the ability to reduce the closing rates when approaching another vehicle more than CCC, thus achieving a smoother interaction with the preceding vehicle. ICC tended to match this ability more than CCC.

The contrast in ICC headway settings between freeways and arterials is interesting. It may be that the longer headway settings on freeways coupled with less traffic and more uniform velocities amongst all vehicles allowed the ICC system to control decelerations when interacting with a preceding vehicle even smoother than that for manual control. Arterials are subject to more stop-and-go driving, due to intersections, stop lights, etc. The lead vehicle is continuously adjusting its velocity to the roadway conditions, thus producing more opportunities for closings compared to freeways. Furthermore, following at a distance could produce higher closing rates than following closely where, in manual driving, there is a tendency to track a vehicle as it decelerates, and in the ICC mode, the system would be operating continuously within a control threshold. Overall, ICC may be considered safety neutral compared to manual driving in terms of average closing rates on freeways and arterials.

3.9.1.2 Time-Headway on Freeways During Closings. Figure 3-83 shows the mean time-headways on freeways during closing situations. Closing situations, as previously defined, are for time-headways less than or equal to 2.4 seconds, and for range rates (closing) less than or equal to – 1.5 m/s. Figure 3-83 indicates that the time-headways for all modes and settings during closing were slightly lower than the time-headways during driving states that were not restricted to closing (See Section 3.9.1.1.). The major difference in the relative headways between these conditions was the lowering of the time-headway for CCC during closing. The net result is that, during closing, ICC overall has the longest time-headways and manual has the shortest time-headways. As was the case previously, the ICC time-headways for each setting were longer than the headways for manual. The time-headways for manual and ICC with a setting of 1.0 second were not substantially different. The longer time-headways suggest a safety benefit.

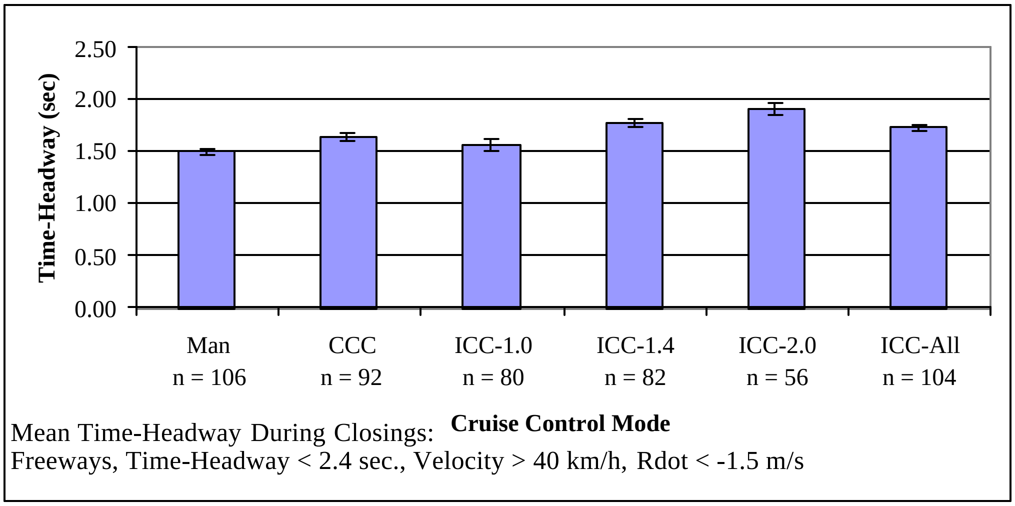

Figure 3-83 Mean Time-Headway as a Function of Cruise Control Mode and ICC Headway Setting during Closings

3.9.1.3 Velocity on Freeways During Closings. Figure 3-84 shows the mean velocities on freeways during closing situations. Figure 3-84 indicates that the mean velocities for all modes during closing were lower than the velocities for all driving, i.e., closing, following, separating, and cruising. (See Section 3.8.2.) The major difference in the relative velocities between these conditions was the lowering of the velocities for CCC during closing. The net result is that, during closing, the velocities for ICC overall and CCC were about the same and greater than that for manual. The ICC velocities for each headway setting during closing were all greater than that for manual. The fact that the velocity differences persisted during closing situations (the ICC difference actually increased) compared to the velocity differences for all driving is a safety concern, particularly with regard to potential collision severity. Thus, a slight safety dis-benefit is suggested for both ICC, including each of the headway settings, and CCC.

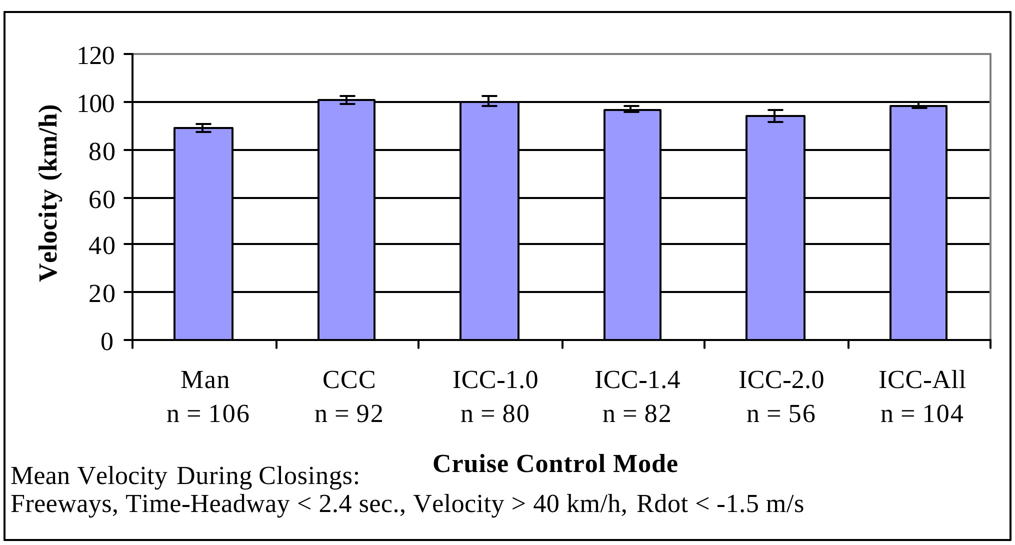

Figure 3-84 Mean Velocity as a Function of Cruise Control Mode and ICC Headway Setting during Closings

The ICC velocities during closing were inversely proportional to the ICC headway setting, although the differences in velocities were not substantial. From a velocity perspective, this headway-setting effect appears to be neutral with respect to safety.

3.9.1.4 Braking Frequency and Braking Force on Freeways During Closings. Figure 3-85 shows a histogram of maximum deceleration associated with each brake press on freeways during closings. There were substantially more brake presses for manual driving compared to both ICC and CCC at each level of deceleration. This result is not surprising since ICC and CCC are restricted to one braking per engagement. Furthermore, ICC was used 58 percent of the time it was available on freeways and spent 5.1 percent of its time in the closing state, compared to 42 percent usage and 6.8 percent of the time in closing for manual. With respect to the total time on freeways in a closing state, the percents for ICC and manual were equal (2.9 percent).

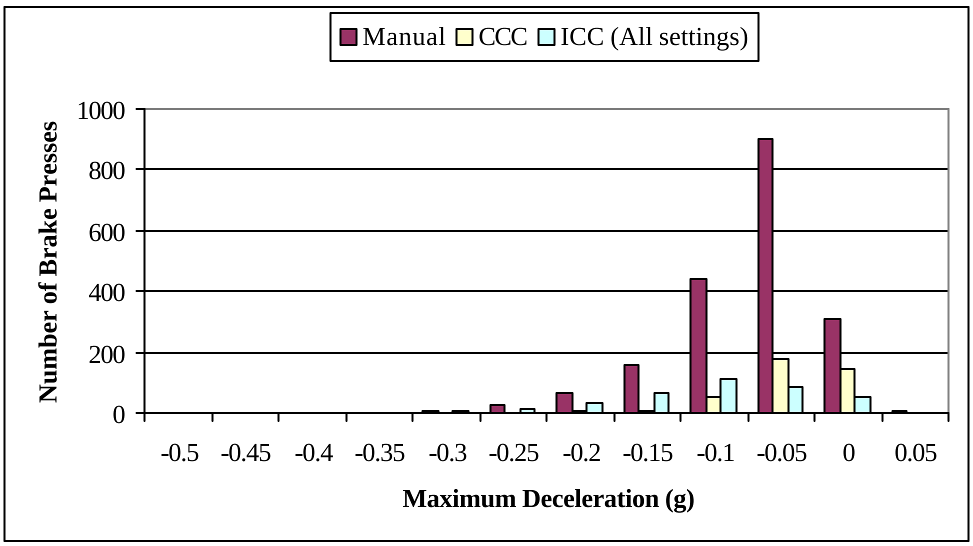

Figure 3-85 Number of Brake Presses Categorized by Maximum Deceleration Associated with Each Brake Press and Cruise Control Mode During Closings

Figure 3-86 shows the proportion of brake presses by mode during closings. About 14 percent of the brake presses for ICC were at deceleration levels greater than or equal to -0.2 g. This compares to about 5 percent for manual and 2 percent for CCC. The proportion for ICC was about double the amount when the states were not restricted to the closing situations. This is a safety concern for ICC as it indicates that during closings braking with ICC was more apt to be harder than braking with manual or CCC. This finding is consistent with the findings for other measures examined later in this section, namely that ICC drivers in certain cases tended to wait for the ICC system to respond to a situation so as to avoid ICC disengagement. A detailed analysis of selected cases of these severe braking events is presented in Section 3.9.2.2.

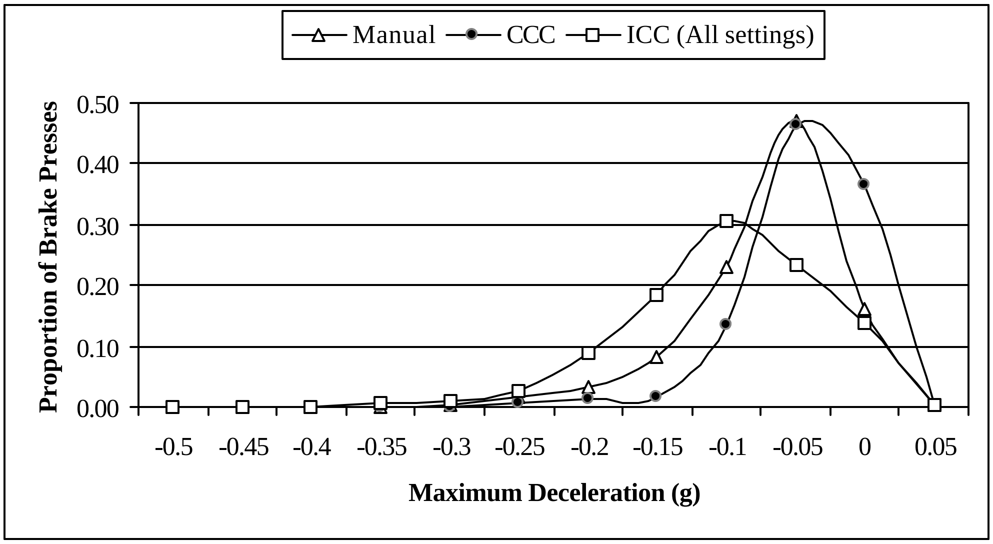

Figure 3-86 Proportion of Brake Presses as a Function of Maximum Deceleration and Cruise Control Mode During Closings

3.9.1.5 Response Time as a Function of Event Criticality on Freeways. As discussed in Section 3.8.5, driver response times were determined with the use of the video analysis tool following an established protocol. Since the primary stimulus was lead vehicle brake lights, most of the events in that analysis can be considered closing situations. In this section, the driver response times are further examined by the criticality of the events. This analysis is restricted to response times on freeways. Critical events are those that would require an immediate response by the driver. It is postulated that critical events would provide a better indicator of true stimulus/response and a stronger basis for determining the potential level of inattentiveness. Response to critical events is not discretionary but rather necessary to avoid a crash. Critical events are defined here as driving situations where a lead vehicle is present and 1) there is a close headway; or 2) the lead vehicle decelerates at a high level; or 3) the host driver responded to the event with a large velocity reductions. These situations are examined separately below.

3.9.1.5.1 Time-Headway on Freeways. The same data from Figure 3-74 are represented in Figure 3-87 in terms of mean time response as a function of time-headway bin. Representing the data in this manner allows not only an examination of the time response trend with time-headway but also a focus on the more critical short time-headways.

The correlation between time-headway and response time can be seen from the figure. Further, this figure indicates that there may be a leveling-off trend at longer headways based on the manual and ICC results for which ample data were available. There are very little data for ICC and CCC in the time-headway bin of 0.0 – 0.5 second and therefore results may not be reliable for comparison between cruise modes. However, the mean time response of 1.2 seconds in the manual mode appears to be a stable indicator for the driving situations involving these time-headways. In the next shortest time-headway bin (0.5 – 1.0 second) there is a substantial amount of data to compare ICC with manual, but not enough data to compare these modes with CCC. The mean response times are approximately 1.5 seconds, and the response time for ICC is greater than that for manual.

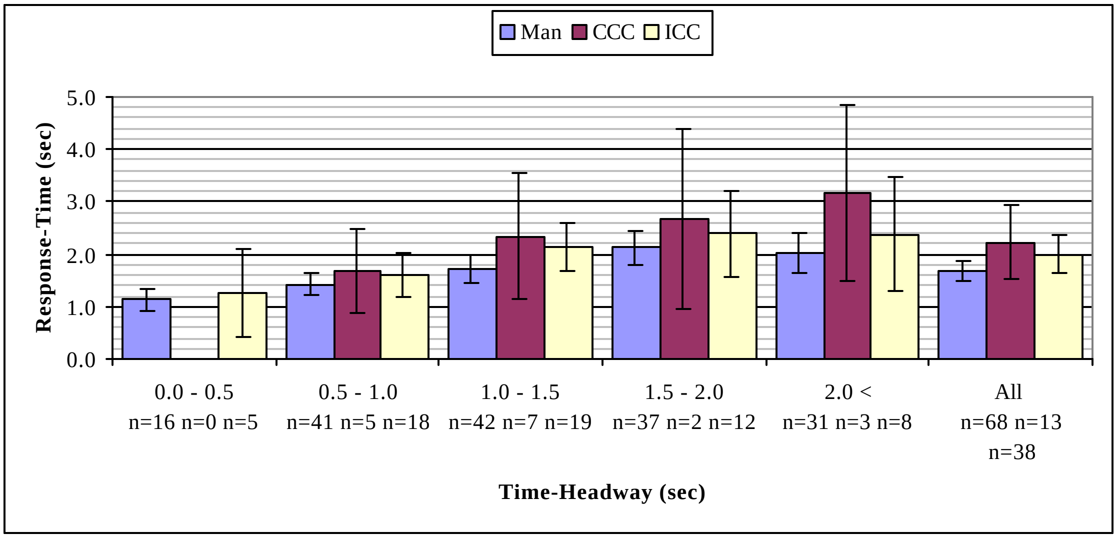

Figure 3-87 Mean Response-Time as a Function of the Level of Time-Headway on Freeways

3.9.1.5.2 Response Time as a Function of Lead Vehicle Deceleration on Freeways. The response times for which lead vehicle deceleration data were available are plotted in Figure 3-88 as a function of the level of the lead vehicle deceleration.

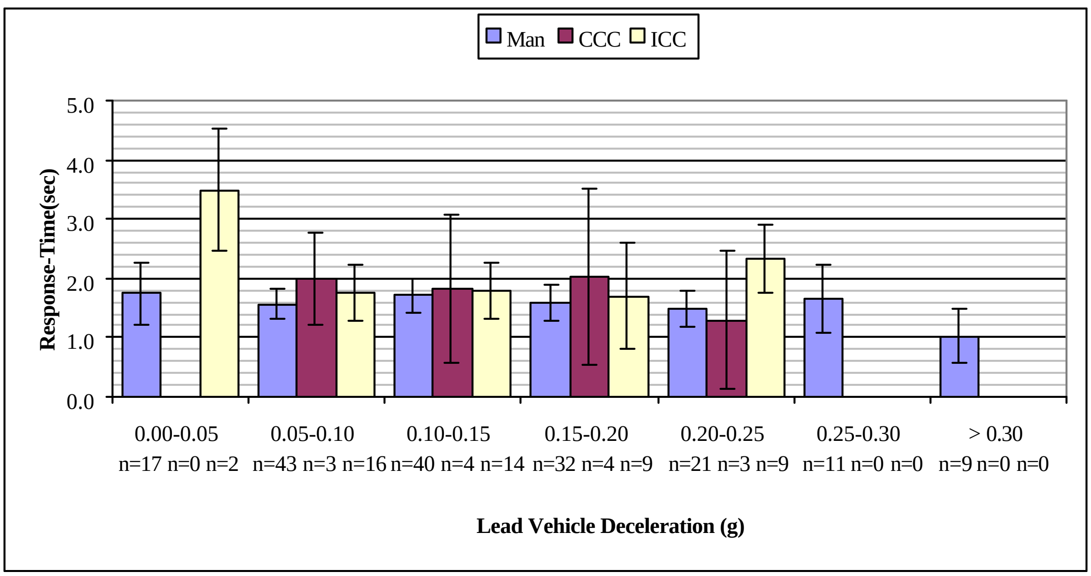

Figure 3-88 Mean Response-Time as a function of the Level of the Lead Vehicle Deceleration on Freeways

The figure indicates that for manual driving, where there is a substantial amount of data; there appears to be a slight trend of reduced response time for higher levels of lead vehicle deceleration. There are very little data in each of the lead vehicle deceleration bins for meaningful comparison between the modes. However, in a number of the bins, there is an indication once again that the time response for ICC driving is greater than that for manual driving. The higher levels of lead vehicle deceleration would, of course, suggest the more critical events. For manual driving, in the 0.20 – 0.25g lead vehicle deceleration bin, the mean response time is approximately 1.5 seconds. This response time drops to about 1.0 second, when the lead vehicle deceleration levels are greater than 0.3 g.

3.9.1.5.3 Response Time as a Function of Velocity Reduction of the Host Vehicle on Freeways. The response times for which velocity reduction data were available are plotted in Figure 3-89 as a function of the level of the host vehicle velocity reduction.

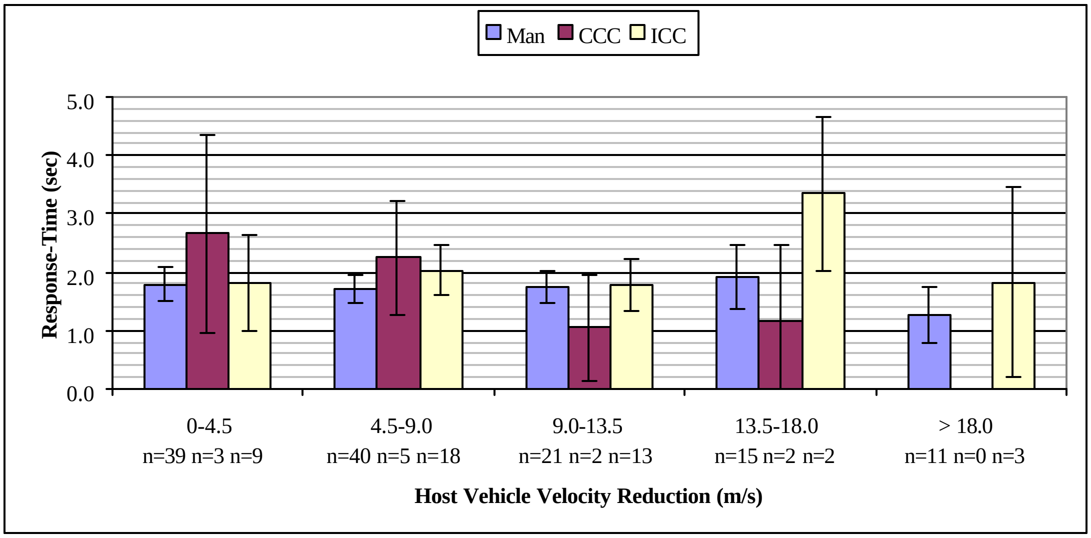

Figure 3-89 Mean Response-Time as a Function of the Level of Host Vehicle Velocity Reduction on Freeways

The figure indicates that for manual driving, where there is a substantial amount of data, there is a possible reduction in response time for higher levels of host vehicle velocity reduction. There are very little data in each of the velocity reduction bins for meaningful comparison between the modes. However, in a few of the bins, there is an indication once again that the time response for ICC driving is greater than that for manual driving. The higher levels of velocity reduction would, of course, suggest the more critical events. For manual driving, in the 9.0-13.5 m/s velocity reduction bin, the mean response time is approximately 1.7 seconds. This response time drops to about 1.3 seconds, when the host vehicle velocity reduction levels are greater than 18.0 m/s.

3.9.1.5.4 Summary of Response Time as a Function of Event Criticality. In an attempt to determine a better indicator of the potential level of inattentiveness due to ICC driving, critical events were defined and examined. The critical events were defined in terms of time headway, level of lead vehicle deceleration, and level of host vehicle velocity reduction.

Although short time headways may lead to critical events, drivers positioning themselves in these situations would be expected to be fully alert and the response times therefore may be considered more demand based than “surprisal”. Any differences between cruise modes during short time headways are thus more likely to be attributed to deliberate action on the part of the driver rather than an indication of inattentiveness.

Situations involving high levels of lead vehicle deceleration appear to be a better basis for determining the potential level of driver inattentiveness. Response times for situations involving levels of deceleration greater than 0.25 g may be considered more likely to be "surprisal" response times. More reliable estimates could perhaps be achieved by eliminating the short time-headway situations which, as discussed above, would eliminate the driver "alert" situations. There were too little data from this field operational test to perform this type of analysis.

Situations involving high levels of host vehicle velocity reduction provide less of a basis for determining driver inattentiveness because: 1) they incorporate different types of events and scenarios; 2) the beginning and end of the appropriate velocity reduction period is not always clear, e.g., situations where the host vehicle makes repeated brakings or situations where there is controlled braking to a stop; and 3) response times to adjacent lane cut-in's and braking with a lane change may not produce any noticeable change in velocities. Nevertheless, the measure is simple, and if used, the level of velocity reduction, based on the above results should probably be greater than 45 feet/second. As stated above, more reliable estimates could perhaps be achieved by eliminating the short time-headway situations.

Driver time responses for critical events, whether based on short time-headways, large levels of lead vehicle deceleration, or large levels of host vehicle velocity reduction, appear to be between 1.0 and 1.5 seconds. This finding suggests that operational response times to critical events in a real world environment appear to be somewhat larger than driver response times found under test conditions such as Taoka. In the limit driver response times to avoid actual collisions may be closer to the Taoka "surprisal" response times, whereas driver response times to warnings from collision avoidance systems may be closer to the "critical event" response times measured in this operational test.

Finally, it is to be noted that the time response results found in this section are also consistent with observations discussed later in Section 3.9.2.2, namely, that ICC drivers tend to wait for the ICC system to respond to a situation so as to avoid ICC disengagement. Whereas the slightly longer response times for ICC may initially appear to suggest a safety disbenefit, the following factors need to be considered: (1) evidence from the driver questionnaires suggests that ICC drivers are well aware of closing events, therefore, the longer response times would not be due to inattentiveness; and (2) results of the braking analysis and critical scenario analysis suggest that only in extremely rare situations do drivers wait so long that severe braking is required. The response time measure is therefore viewed as a safety concern, but not an indication of a general safety problem with the ICC system.

3.9.1.6 State Space Boundary Crossings on Freeways. State space boundary crossings provide another surrogate measure of safety during closing situations. Boundaries are first defined in terms of the relative range and range-rate between a lead vehicle and the vehicle hosting the ICC system. These boundaries represent the initial range and range rate conditions required to bring a following vehicle, closing in on a lead vehicle at a constant rate and then braking at a constant deceleration level, to the range indicated by the intercept of that curve with the ordinate. Furthermore, the initial conditions may be interpreted as initial conditions for potentially hazardous driving scenarios. The scenarios may be a particular driving situation or condition that suddenly confronts the driver of the host vehicle such as a cut-in or a lead vehicle deceleration. Other safety surrogates such as headways, velocities, and deceleration levels, have been used extensively in past operational tests and evaluations, (Perez, 1996; Fancher, 1995) and have provided valuable information on the potential safety effectiveness of the tested device. Further, the phase plane method has been used by researchers (Fancher, 1996) as a method for presenting field operational test data. The state space boundary concept has the advantage of integrating a number of important accepted measures of safety into a single measure and in a manner that can be related to specific driving scenarios. As such, more direct safety inferences may be drawn from operational test data, particularly as it relates to the pre-crash scenarios for which an abundance of collision data has been recently accumulating. (Najm, 1998)

Appendix J, *State Space Boundary Definitions* provides a further description of the state space boundaries including specific boundaries for specific pre-crash scenarios. (See next section for description of pre-crash scenarios.) Appendix K, *State Space Boundary Crossing Analyses* conducts additional state space boundary crossing analyses for four specific pre-crash scenarios based on data from the field operational test.

The general form of the equation for the boundaries is:

$$R = Rm + \dot{R}^2 / 2a$$

where R is the range between the lead and host vehicles, $\dot{R}$ is the range rate, R_m is the minimum range separation where the boundary crosses the range axis, and a is the deceleration constant in g's. The parameters for boundaries used for this analysis are given in Table 3-47. Other parameters may be used for different analyses. Appendix K gives examples of other parameters that are used relative to this study.

Table 3-47 Boundary Parameters

Boundary	R_m	a
B5	13.4 m	0.10
B4	8 m	0.10
B3	4 m	0.10
B2	0 m	0.15
B1	0 m	0.70

Figure 3-90 shows the five boundaries plotted on a range, range-rate diagram. Whenever the range and range-rate of an ICC vehicle placed it below one of the five boundaries, a boundary crossing was recorded. Figure 3-91 shows the average, over drivers, of the number of crossings on freeways divided by the kilometers driven on freeways, i.e., the mean boundary crossings per kilometer.

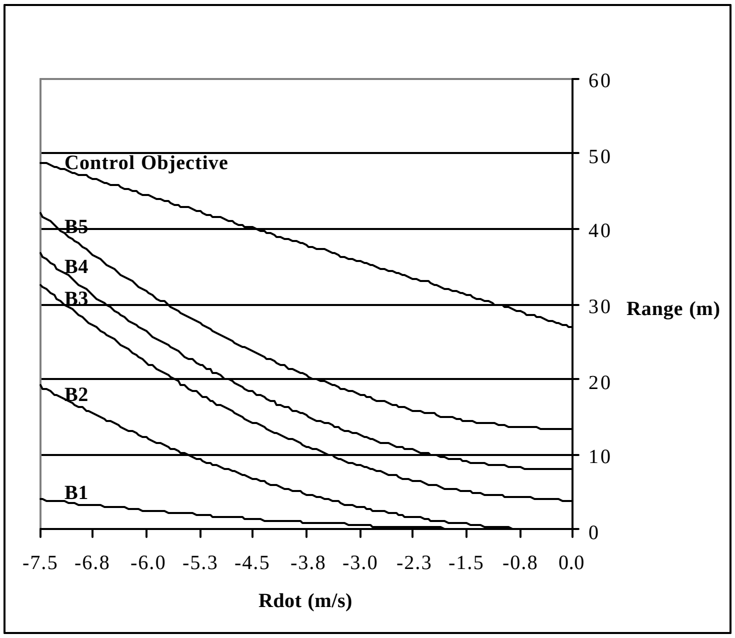

Figure 3-90 State Space Boundaries as a Function of Range and Range-Rate

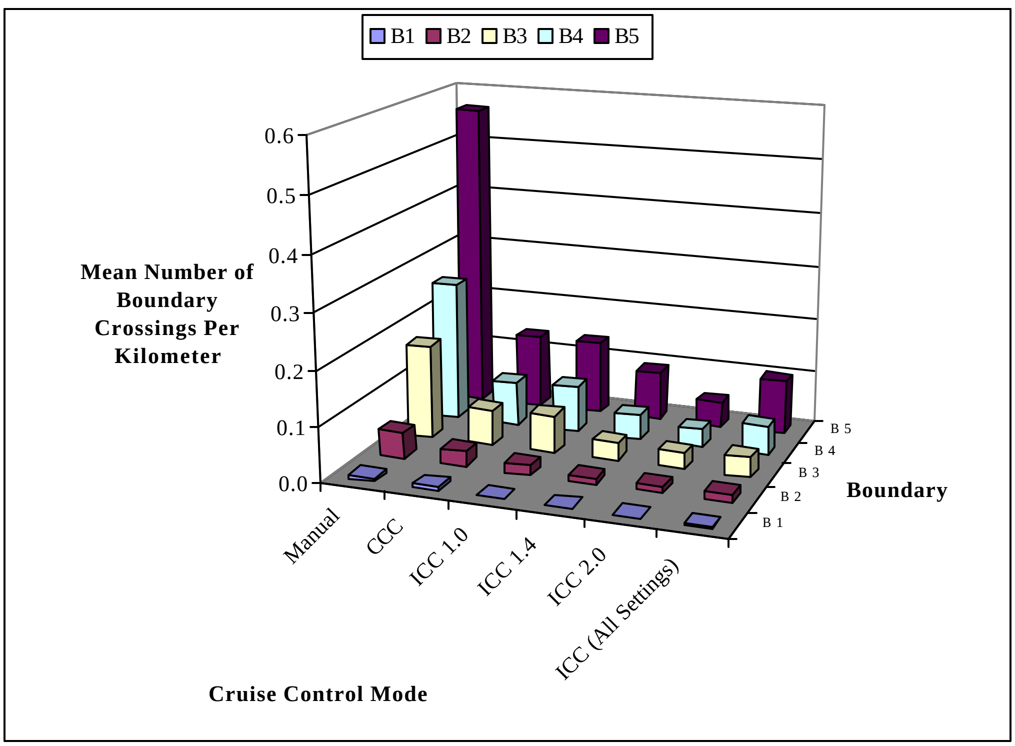

Figure 3-91 Mean Number of Boundary Crossings Per Kilometer as a Function of Cruise Control Mode and State Space Boundary

Boundary crossings, particularly for the lower boundaries, were relatively rare. Furthermore, some drivers had many, and some drivers had none. However, there were a sufficient number of crossings for boundaries 3, 4, and 5 to justify a cautious inferential statistical analysis. An analysis of variance on the log of the number of boundaries crossed per kilometer was performed with cruise mode and boundary as within subject variables and cruise mode and age group as between subject variables. A three-way interaction of cruise mode, boundary, and age group was obtained, $F(8, 376) = 8.0$, $p < 0.05$). The findings are best understood by reference to Figure 3-92.

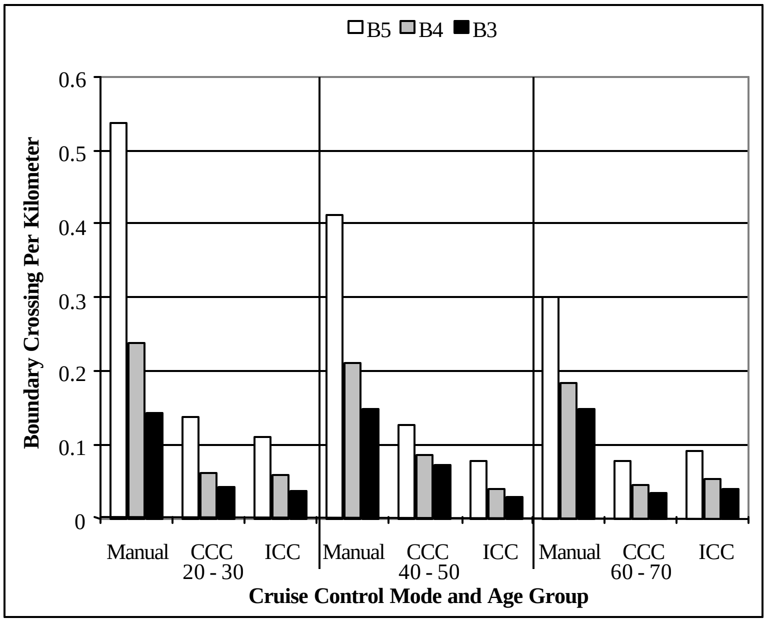

Figure 3-92 State Space Boundary Crossings Per Kilometer as a Function of Cruise Control Mode and Age Group for Boundaries 3, 4, and 5

Because the boundaries were not independent, boundary 5 was crossed more than 4, which was crossed more than 3. In manual mode, young drivers were more likely to cross boundaries 5 and 4 than were drivers from either of the other age groups. Age group differences were attenuated with CCC and almost eliminated with ICC. ICC and CCC greatly reduced the differences between boundaries.

If crossing these boundaries is assumed to indicate an increased crash risk, then ICC reduces that risk not only relative to manual driving, but also relative to CCC. The comparison to CCC is impressive, given that ICC was used in somewhat heavier traffic than CCC. That is, if the reduced rate of boundary crossings with CCC were attributed to encountering less traffic when in CCC, rather than to inherent CCC safety features, then the crossing rate with ICC would be expected to be equal to or higher than that with CCC. That the ICC rate was substantially lower than CCC is a strong indicator of a safety benefit for ICC attributable to its headway and velocity control features. Furthermore, when younger drivers use ICC, their crash risk is almost equal to that of older, presumably more cautious, drivers. Thus ICC may provide a particular safety benefit to younger, more risk prone drivers.

We have shown the number of boundary crossings per kilometer for manual, CCC, and ICC. A similar analysis was conducted using the percent of time within each boundary as the dependent variable. The results of the latter analysis are shown in Figure 3-93. As was the case for the number of boundary crossings per kilometer, cruise control mode, boundary, age group, and the interaction of these factors yielded statistically different means. Clearly, far more time was spent below boundary 5 than the other boundaries. The age group differences are more pronounced using percent of time as the dependent measure, and these differences are greatest for boundary 5. The differences between CCC and ICC are small with respect to percent of time.

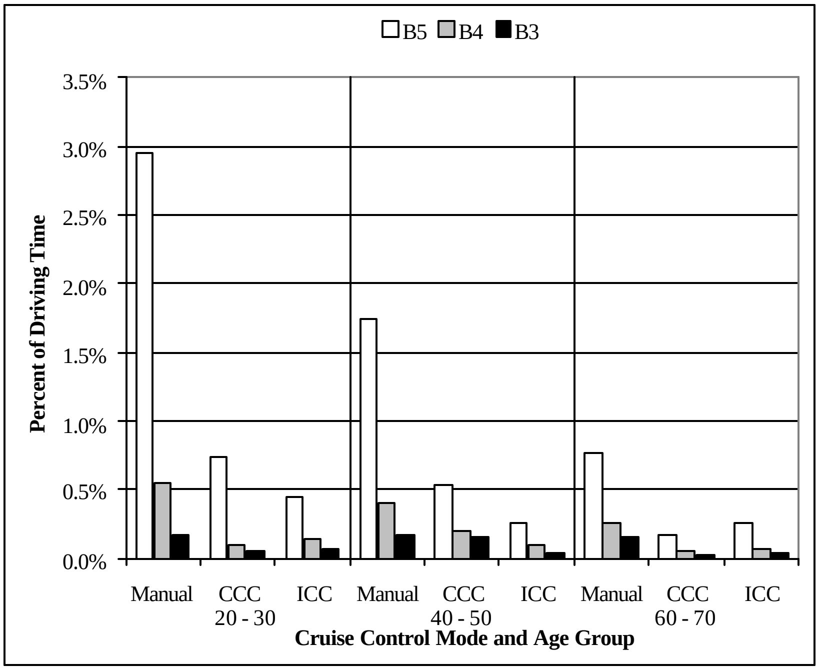

Figure 3-93 Percent of Time on Freeways within Boundaries as a Function of Age Group and Cruise Control Mode

Summary Observations Regarding ICC Influence on State Space Boundary Crossings – Freeways: The analyses of the boundary crossing data suggest a potential safety benefit for ICC. The safety benefit may be inferred from both the number of crossings per kilometer, and the percent of driving time below the boundaries. When percent of time below the boundaries is considered, the safety benefit of ICC over CCC is not as evident. However, it is important to note that ICC was used more than twice as much as CCC, and was presumably used in heavier traffic where CCC would not be used. Thus the finding that time below boundaries did not increase with ICC relative to CCC may be indicative of a safety benefit.

3.9.1.7 Close Calls

3.9.1.7.1 Close Call Frequency on Freeways and Arterials Another surrogate for crashes that was examined was close calls. The close call analysis was adopted from a technique developed by Dingus, et al., 1995. A close call was defined as any event which met the "near encounter" or "brake intervention" video trigger requirements, and that represented (in the judgement of the video analyst) a potential interaction with another vehicle, or a near run-off-road event. The video analysis tool, described in Appendix H, facilitated the identification and recording of close call event type, potential crash severity, and hazard proximity.

Potential crash severity was assigned based on the type of close call and the velocity at which the close call occurred. The analyst identified the event type using an on-screen classification tree (described and shown in Appendix I) and the video tool assigned severity based on velocity. The severity was categorized on a scale from 1 to 4. Points on the severity scale were:

1. Minor – Potential for a crash limited to property damage and no injuries.

2. Marginal – Potential for a crash with minor injuries that would not require hospitalization.

3. Critical – Potential for a crash with severe injuries that would require overnight hospitalization, but where permanent disabling injuries would be unlikely.

4. Most Severe – Potential for a crash with a fatality or permanent disabling injury.

The analyst also rated the proximity to a crash using on the following classification scheme:

1. Near Miss – The driver took immediate evasive action to prevent a crash.

2. Hazard Present – The vehicle nearly missed an object that was close enough to represent a hazard to the ICC vehicle, but evasive action was not taken or necessary.

3. No Hazard Present – There was a driving error, such as a deviation into an oncoming lane, but there was nothing there to crash into, and immediate evasive action was not required.

The number of close calls on freeways, as a function of severity and proximity, is provided in Table 3-48. Further information on the *critical* and *most severe* near misses including braking forces and minimum approaches are presented and discussed later in this section.

Table 3-48 Close Calls on Freeways

Severity Potential	***Proximity***			
	Near miss	Hazard present	No Hazard Present	Total
Minor	0	0	2	2
Marginal	0	17	1	18
Critical	11	2038	8	2057
Most Severe	5	118	0	123
Total	16	2173	11	2200

The number of close calls, as a function of severity and proximity, for arterials is provided in Table 3-49.

Table 3-49 Close Calls on Arterials

Severity Potential	***Proximity***			
	Near miss	Hazard present	No Hazard Present	Total
Minor	3	5	0	8
Marginal	0	23	0	23
Critical	4	1196	8	1208
Most Severe	5	421	4	430
Total	12	1645	12	1669

There were 92 drivers for whom video data were available and who drove on freeways in manual, CCC, and ICC modes. The number of close calls was adjusted for the distance each driver drove in each mode, and transformed to a rate, namely, close calls per million vehicle kilometers (MVkm). As shown in Figure 3-94, the rate was highest for manual driving, and similar for CCC and ICC. The mode effect was statistically reliable F (2, 172) = 22.4, $p < 0.001$). The rate did not differ significantly between CCC and ICC.

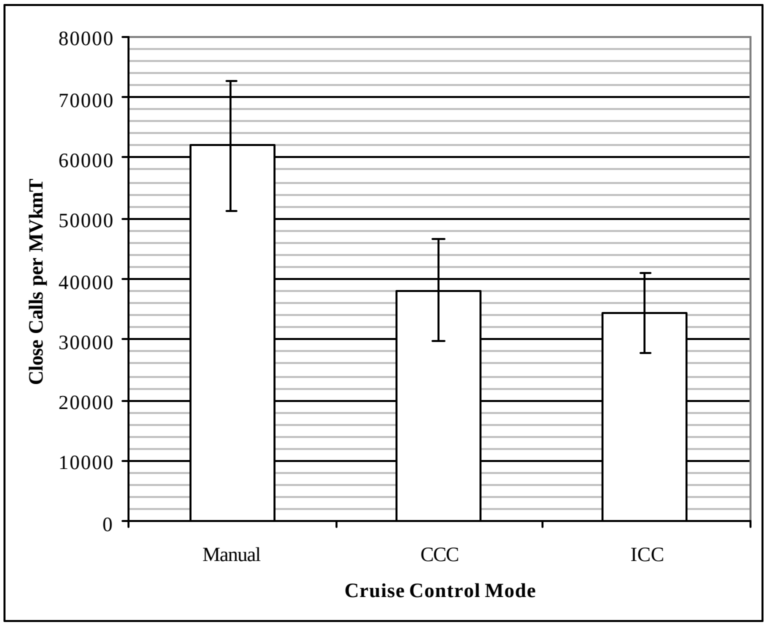

Figure 3-94 Number of Close Calls per Million Vehicle Kilometers on Freeways as a Function of Cruise Control Mode (N = 92)

As can be seen in Figure 3-95 the youngest age group had about 50 percent more close calls than other age groups, which did not differ from each other. The overall age effect was statistically reliable, F (2, 86) = 4.4, $p < 0.05$.

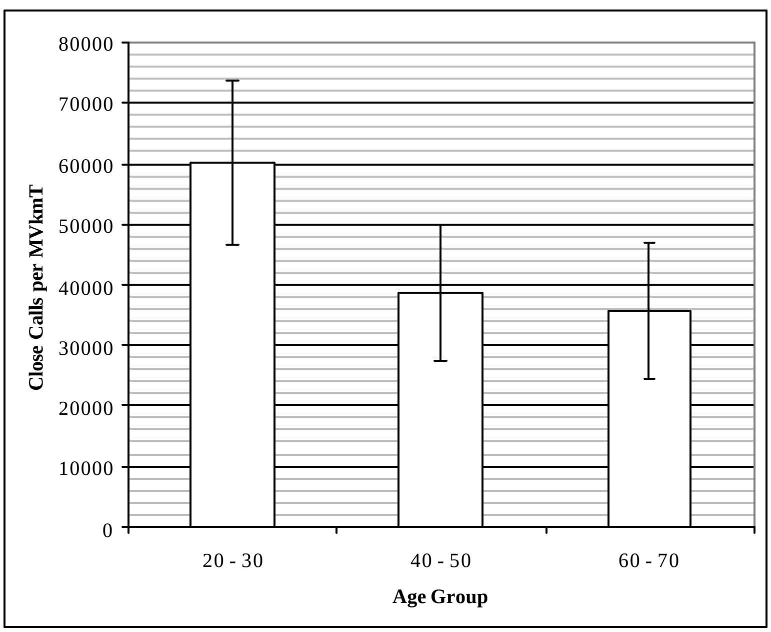

Figure 3-95 Number of Close Calls per Million Vehicle Kilometers on Freeways as a Function of Age Group

There were 44 drivers who drove on arterials in manual, CCC, and ICC modes. As shown in Figure 3-96, close calls per MVKm for manual driving were less than on freeways. In a marked reversal from the trend seen on freeways, on arterials, the two cruise control modes were associated with more close calls per million vehicle kilometers compared to manual. An examination of the possibility that the 44 drivers exhibited unique driving behavior, whether on arterials or freeways revealed the contrary. Namely, compared to the larger set of drivers, they showed the same close call trend on freeways and usage rates for different levels of service on arterials. The mode effect was statistically reliable, $F(2, 76) = 3.7$, $p < 0.05$. The CCC and ICC did not differ significantly from each other.

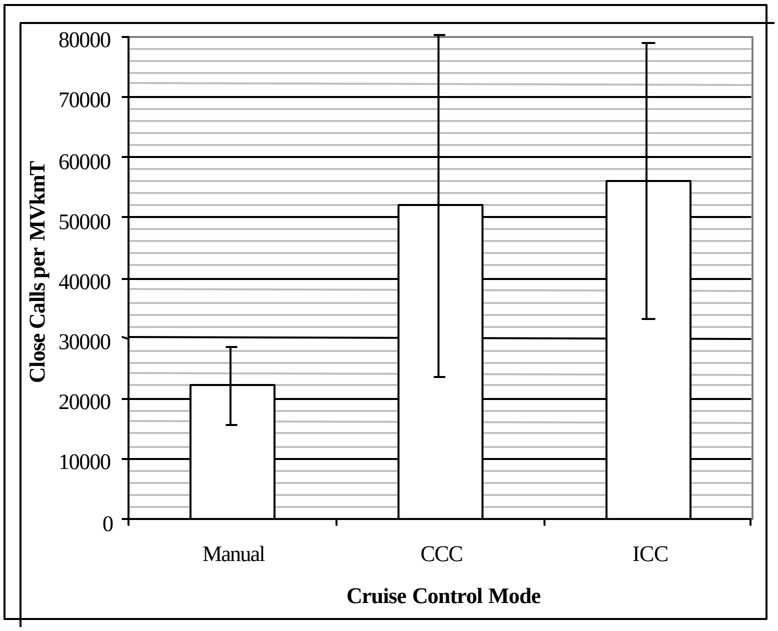

Figure 3-96 Number of Close Calls per Million Vehicle Kilometers on Arterials as a Function of Cruise Control Mode (N = 44)

Figure 3-96 is based on the means and standard errors for 44 drivers who used all three modes on arterials. As can be seen in Figure 3-97 over 40 percent of the drivers who used ICC and CCC on arterials had no close calls. Another group of drivers that represented about 33 percent of the sample had close calls at a rate of between 150,000 and 300,000 per million kilometers. These data suggest that cruise control, either ICC or CCC, may increase the driving risks of some arterial users. There were drivers who had a high frequency of close calls in manual mode who had few or none when using ICC. Thus it appears that ICC moderated the aggressive behavior of some drivers. If a driver had a high frequency of close calls when using ICC or CCC, that driver invariably had a high frequency of close calls when driving manually as well. However, for some drivers with a high rate of close calls in manual, cruise control seemed to have increased the probability of close calls on arterials. A similar trend, for a few drivers to have an inordinately high rate of close calls, was observed on freeways, but as can be seen in Figure 3-98, the distribution of close call rates was more normally distributed. On freeways, ICC seems to have had a more moderating effect on driver behavior than it did on arterials.

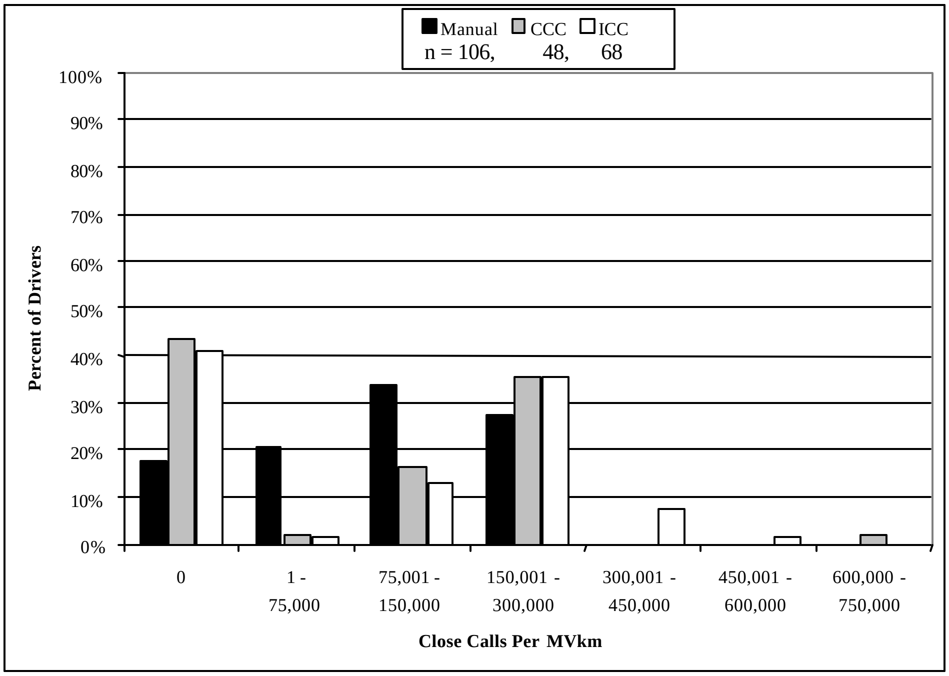

Figure 3-97 Distribution of Drivers Contributing Close Calls on Arterials

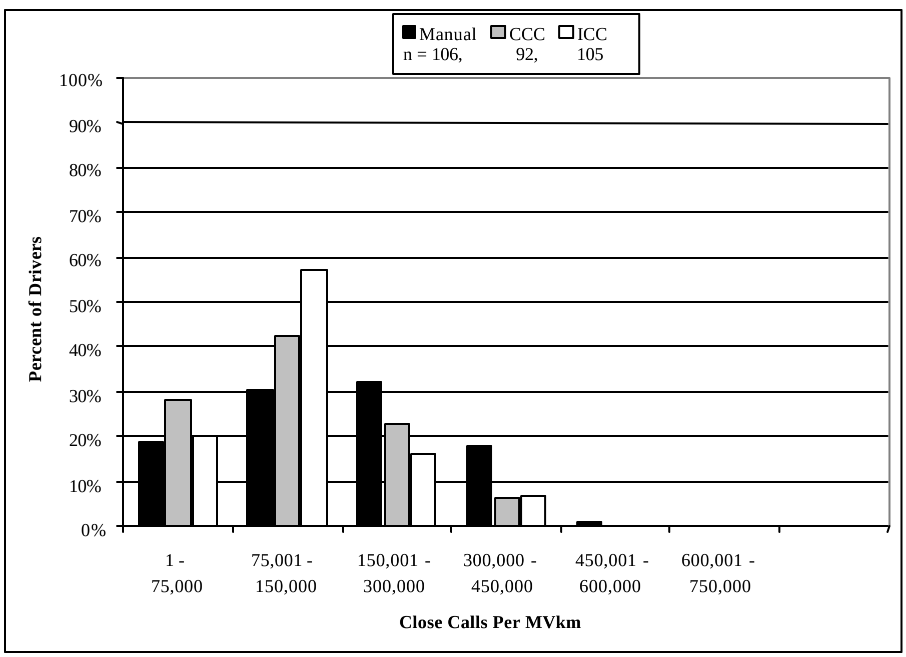

Figure 3-98 Distribution of Drivers Contributing to Close Calls on Freeways

In summary, on freeways ICC appears to be associated with a lower frequency of close calls, either because it is used where there is less traffic to present a hazard, or because it moderates aggressive driving behavior. On arterials, there was a subset of about half the ICC and CCC users who appear to increase their rate of close calls when they use either cruise control type on arterials. A moderating effect appears plausible for some drivers. With regard to the close call measure, therefore, ICC driving (as well as ICC) seems to be associated with less safe driving by some drivers on arterial roadways.

3.9.1.7.2 Close Call Severity on Freeways and Arterials. Severity summary statistics are provided in Table 3-50 and Table 3-51, for freeways, and arterials respectively. A severity of 1 represented a potential for crashes with minor damage and no injuries. A severity of 4 represented a potential for a severe crash with fatalities. There were no statistically reliable differences in severity of close calls on freeways, or arterials, as a function of cruise control mode, age group, or previous cruise control use.

Table 3-50 Freeway Close Call Mean Severity by Cruise Control Mode

Mode	*Mean Severity*	*Standard Error*	*Number of Drivers Contributing*	*Average Number of Close Calls per Driver*
Manual	3.05	0.02	86	16.5
CCC	3.02	0.01	67	3.8
ICC	3.05	0.03	84	6.2

Table 3-51 Arterial Close Call Mean Severity by Cruise Control Mode

Mode	*Mean Severity*	*Standard Error*	*Number of Drivers Contributing*	*Average Number of Close Calls per Driver*
Manual	3.23	0.04	87	14.8
CCC	3.18	0.07	31	1.0
ICC	3.14	0.08	43	3.2

Proximity of Close Calls Close call proximity summary statistics are provided in Table 3-52 for freeways, and Table 3-53 for arterials. There were no statistically reliable differences in close call proximity to hazards, either on freeways, or on arterials, as a function of mode, age group, or previous cruise control use. A proximity of *1* represented a *near miss*, a proximity of *2* represented a *hazard present*, and a proximity of *3* indicated *no hazard present*.

Table 3-52 Freeway Close Call Mean Proximity by Cruise Control Mode

Mode	*Mean Proximity*	*Standard Error*	*Number of Drivers Contributing*	*Average Number of Close Calls per Driver*
Manual	2.01	0.006	86	16.5
CCC	2.00	0.004	67	3.8
ICC	2.00	0.008	84	6.2

Table 3-53 Arterial Close Call Mean Proximity by Cruise Control Mode

Mode	*Mean Proximity*	*Standard Error*	*Number of Drivers Contributing*	*Average Number of Close Calls per Driver*
Manual	2.01	0.008	87	14.8
CCC	2.00	0.003	31	1.0
ICC	2.00	0.005	43	3.2

Most severe close calls, close calls with a severity rating of 4, would be of the highest safety concern. Any new system that increased the risk of *most severe* close calls would be of great concern. On freeways, the rate of *most severe* close calls varied with cruise control mode: the rate was lowest for CCC (953 per MVkm), followed by ICC (2125 per MVkm) and Manual (4569 per MVkm). The cruise control mode effect was statistically reliable, F (2, 190) = 5.0, $p < 0.01$, however, the difference between ICC and CCC was not statistically reliable. The only other significant finding with the *most severe* close calls was that those who said they were previous cruise control users had a much higher rate of *most severe* close calls (3944 versus 1153 per MVkm), F (1. 95) = 6.3, $p < 0.05$. Note that there were 123 *most severe* close call cases, as indicated in Table 3-48 that were examined in this analysis.

On arterials the lowest rate of *most severe* close calls was in manual mode (9454 per MVkm), followed by CCC (16277 per MVkm), and ICC (22705 per MVkm). The difference between manual and ICC was statistically reliable, F (1, 62) = 6.5, $p < 0.05$. The 430 *most severe* close call cases, as indicated in Table 3-49, were included in this analysis. Because of the small number of drivers with observations in all three modes, CCC was not included in the analysis of variance. As with close calls in general, it was a minority of drivers who generated the majority of *most severe* close calls in CCC and ICC modes. As can be seen in Table 3-54, there was a much higher percentage of drivers with *most severe* close call rates over 1,000 per MVkm in manual mode, than there was in either the CCC or ICC modes. Thus, the overall high rates of *most severe* close calls in the CCC and ICC modes were the result of fewer than 20 drivers who exhibited worrisome behaviors. There was only one driver who had a high rate of *most severe* close calls in ICC who did not also have a high rate of *most severe* close calls in the manual mode as well.

The freeway close call data give no reason for ICC safety concerns. If anything, ICC may have reduced the number of close calls that some drivers would have had otherwise. On arterials, there appears to be subset of drivers who have an inordinate number of close calls using cruise control (both ICC and CCC). These drivers had the highest close call rates with ICC, though this may have been because they used ICC in heavier traffic conditions than CCC. The majority of drivers saw a decrease in the rate of *most severe* close calls on arterials, but the subset of high risk drivers drove the mean rates for CCC and ICC far above the mean rate for manual. For this subset of drivers, the increased convenience offered by ICC systems may also increase the risk of crashes. This increase includes severe crash risk.

Table 3-54 Proportion of Drivers with High Rates of *Most Severe* Close Calls on Arterials

	Manual	*CCC*	*ICC*
Number of drivers who drove in mode on arterials	105	48	68
Percent of drivers who drove in mode and had a most severe close calls rate greater than 1000 per MVkm	66%	19%	29%

The *critical* and *most severe near miss* close calls are examined individually next for freeways and arterials. The very small number of these cases (see Tables 3-48 and 3-49) did not permit a statistical analysis.

3.9.1.7.3 Analysis of Critical and Most Severe Near Miss Close Calls on Freeways. This section examines the following close calls on freeways that were rated by the analyst as *critical* or *most severe near misses*:

- manual Driving (8 cases),
- CCC Driving (0 cases),
- ICC Driving (8 cases), and
- total (16 cases).

A can be seen in these data, there were very few cases of *critical* and *most severe near miss* close calls. The individual cases are examined next by mode.

Manual Of the eight manual cases, two occurred during heavy traffic, two involved somewhat reckless driving (crossing over solid line, high velocity), one occurred during rain as the host vehicle accelerated and passed the lead vehicle on the left, one occurred at a construction site as the host vehicle moved onto the left shoulder, one involved a lane change prior to an exit ramp, and one involved a heavy braking (0.6g) as the lead vehicle decelerated to slow down for a work crew on the side of the road.

CCC There were no cases.

ICC Case 1, Cut-in[4] - The initial conditions for this cut-in occurred at a distance of 9 meters and a closing rate of 5.5 m/s. The ICC driver braked at a 6 meter range and at a level of 0.5 g. The minimum approach was 3 meters. Use of the ICC did not appear to contribute to the hazard in this case.

Cases 2&3, Cut-ins - In both cases, the lead vehicle did not cross completely into the lane ahead of the host vehicle. In both cases the host vehicle driver braked hard (0.24 g and 0.30 g) even though there was plenty of warning of the cut-ins. The minimum approach in case 2 was 6 meters. Use of the ICC did not appear to contribute to the hazard in either case.

Case 4, Cut-in - The lead vehicle signaled 3 seconds before crossing into the lane ahead of the host vehicle. The host vehicle braked about 2 seconds after this signal. The initial conditions for this cut-in were: a range of 6 meters, a closing rate of about 3 m/s, and vehicle velocities of about 30 m/s. The host vehicle braked at 0.1 g. The case ended with a close approach as the lead vehicle moved slowly back into the right lane. The minimum approach was 4.5 meters. Use of the ICC may have contributed to the hazard in this case since the driver appeared to have delayed braking to see if the ICC system could resolve the developing situation.

Case 5, Lane Change - In this case the host vehicle driver changed lanes and braked at 0.21 g to come to a stop in the breakdown lane. The velocity in the breakdown lane was initially 23 m/s. The closest approach to a lead vehicle was 21 meters. Use of the ICC did not appear to contribute to the hazard in this case.

Case 6, Approach - In this case, which occurred at night, the host vehicle driver decelerated and followed a lead vehicle into the breakdown lane. Use of the ICC did not appear to contribute to the hazard in this case.

Case 7, Lead vehicle decelerating - The driver of the host vehicle braked early (23 meter range and before the scenario developed) at a level of 0.22 G. The driver then moved off the side of the road due to road construction. Use of the ICC did not appear to contribute to the hazard in this case.

Case 8, Lead vehicle stopped - The host vehicle braked at 0.4g to avoid a lead vehicle stopped ahead. This occurred at night and there was a line of near-stopped vehicles in the left lane as the host vehicle passed by. The ICC system did not respond to the vehicle ahead because the driver braked early disengaging the system. The host vehicle velocity was initially 20 m/s and the minimum approach (near stop) was 4.5 meters. Use of the ICC did not appear to contribute to the hazard in this case.

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[4] "Cut-in" here refers to a classification of pre-crash scenarios that is used in this study to categorize particular driving situations. For this classification, the lead vehicle cuts in front of the host (ICC) vehicle. Section 3.9.2.1 defines and describes the pre-crash scenarios.

Summary Observations Regarding ICC Influence on Near Misses – Freeways Very few *critical* or *most severe near miss* close calls were found. Use of the ICC may have contributed to the hazard in one, of eight of these close call cases. In this one case, the driver appeared to have delayed braking to see if the ICC system could resolve the developing situation.

3.9.1.7.4 Analysis of Critical and Most Severe Near Miss Close Calls on Arterials. This section examines the following close calls on arterials that were rated by the analyst as *critical* or *most severe near misses*:

- manual Driving (7 cases),
- CCC Driving (1 case),
- ICC Driving (1 case), and
- total (9 cases).

There was only one ICC *near miss* close call on arterials. The individual cases are examined next by mode.

Manual Of the seven manual driving cases, three occurred near intersections with the host vehicle driver braking early to resolve the developing situation, two occurred on two-lane roadways, one occurred at an intersection where another driver entered from the left into the center lane and the host vehicle passed in the left lane, and the last one occurred at an intersection where a tractor trailer entered from the right in front of the host vehicle which then passed on the right.

CCC The CCC case occurred on a two-lane roadway where *lead vehicle* (emergency vehicle) *decelerated* and pulled off to the side of the road. The host vehicle braked early, i.e., at a range of 45 meters in this case.

ICC The ICC close call was mostly a *cut-in* that occurred in the presence of an intersection at night. The host vehicle was travelling at 24 m/s and the cut-in vehicle was travelling at 21 m/s. The initial range at cut-in was 6 meters. The ICC responded to this situation by decelerating at 0.05 g. The driver then intervened and braked at 0.18 g. The scenario involved other stages including eventually a *lead vehicle decelerates* for a left turn. The final conditions were a range of 4.5 meters and a host vehicle velocity of 14 m/s.

Summary Observations Regarding ICC Influence on Near Misses - Arterials There was only one ICC *near miss* close call on arterials. In this case, the driver may have waited somewhat to see if the ICC system would resolve the cut-in situation, but responded quickly when it was apparent that braking intervention was required. Thus, the ICC system may have been a contributing factor in this close call.

Appendix L, *Video Analysis of Critical Pre-Crash Scenarios* examines additional driving scenario cases individually. These cases were the results of either high brakings or near encounters (as determined by the triggering criteria for these video episodes). The net result of all these cases are summarized and discussed in Section 3.9.2.1.

3.9.1.7.5 Close Calls Summary On freeways there were less close calls and less *most-severe* close calls for ICC compared to manual driving, suggesting a safety benefit. On arterials there were more close calls and more *most-severe* close calls for ICC compared to manual driving, thus presenting a safety concern.

3.9.1.8 Summary of Driving Behavior During Closing States. The above measures indicate that during closing states that may be considered safety-critical, ICC showed signs of a positive safety effect including longer headways, fewer boundary crossings, and fewer close calls. On the other hand, there were some safety concerns. Compared to manual driving, ICC showed higher velocities, proportionately harder braking, and longer time responses to critical events. Compared to CCC, ICC had lower closing rates and longer headways but proportionately harder brakings. The measures further indicate that there is a parity between ICC and CCC during safety-critical situations in terms average velocities, boundary crossings, and close calls. To further understand the implications of the results from these safety-critical measures, as well as the results of the measures for overall driving, specific pre-crash scenario types are examined and analyzed in the next section.

3.9.2 Pre-Crash Scenarios

3.9.2.1 Occurrence of Pre-Crash Scenarios on Freeways. Recently, information on *pre-crash scenarios* has been collected and added to national crash databases to enhance the utility of the databases (Najm, et al., 1998; Wiacek and Najm, in press). These scenarios are defined in terms of the driving situations and dynamics that immediately preceded police reported crashes. The pre-crash scenario information is expected to lead to a better understanding of the causes and circumstances of collisions, as well as to a more accurate projection of the effects of proposed collision countermeasures. As a result of this new information, it is now possible to quantify the pre-crash circumstances for different collision types. Given the functional capabilities of the ICC system, rear-end collisions were deemed the most relevant collision type for consideration in the ICC evaluation.

In the ICC FOT, no pre-crash scenarios occurred that led to actual crashes. However, pre-crash scenario types do occur in everyday driving without being followed by a crash. It is the occurrence of these everyday-driving pre-crash scenario types that are the subject of this section. The probability of the pre-crash scenario types occurring in the normal course of driving has not been widely studied. The data available from the ICC FOT presents a unique opportunity to investigate this issue. Therefore, this section reports the rate of four pre-crash scenarios types that occurred during the field operational test. Also reported is how these probabilities varied as a function of cruise mode.

The four relevant pre-crash scenarios are:

- lane change,
- cut-in,
- approach, and
- lead vehicle deceleration.

The first three scenarios are defined relative to the states and transitions. A **lane change pre-crash scenario** is a lane change scenario (active acquire, drop or switch from the transition definitions given in Section 2.6.1) whose "after" sub-state is one of the following: *closing-close-rapidly*, *closing-close-moderately*, *closing-middle-rapidly*, *closing-middle-moderately*, *closing-far-rapidly* or *closing-far-moderately*. A **cut-in pre-crash scenario** is a cut-in scenario (passive acquire or switch) whose "after" sub-state is one of the following: *closing-close-rapidly*, *closing-close-moderately*, *closing-middle-rapidly*, or *closing-middle-moderately*. An **approach pre-crash scenario** is a cut-in scenario whose "after" sub-state is either *closing-far-rapidly* or *closing-far-moderately*. The latter two together account for all the closing sub-states for the passive acquire or switch. Each of the pre-crash scenarios thus require a time-headway between the ICC vehicle and the lead vehicle of less than 2.4 s, and a closing rate of at least 1.5 m/s.

The **lead vehicle deceleration pre-crash scenario** is defined here as the occurrence of situations where the lead vehicle decelerates greater than 0.25 g, the time-headway between the ICC vehicle and the lead vehicle is less than 2.4 s, and the closing rate is at least 1.5 m/s. Thus, the **lead vehicle deceleration pre-crash scenario** is intended to capture only those situations where the lead vehicle performs an aggressive braking maneuver to which the host (following) vehicle is likely to respond.

As noted earlier, the rate of occurrence of pre-crash scenarios is postulated in this analysis to be related to the rate of occurrence of collisions. The focus here is therefore on the relative occurrence of the pre-crash scenario types by mode.

The four scenario types are distinct and discernible and it is clear that they also represent different actions on the part of the host vehicle driver. The actions may be either precipitating actions, or response actions, or both. For example, **cut-ins** and **lead vehicle decelerations** are precipitating actions by the lead vehicle driver, while **lane changes** are precipitating actions by the host vehicle driver. **Approaches** may be considered precipitating actions by either or both drivers.

With **lane change pre-crash scenarios**, a major consideration is the analyses of the situation before the lane change. On the other hand, with **cut-in**, **lead vehicle deceleration**, and **approach pre-crash scenarios**, a major consideration is the analysis of the post-maneuver situation that confronts the host vehicle driver. Lane changes and cut-ins were previously examined in Sections 3.7.7 and 3.7.9, respectively, with these considerations in mind.

It should be further noted that a response type action possible to a **cut-in, approach,** *or* **lead vehicle deceleration pre-crash scenario** is a lane change maneuver. The precipitating actions and the subsequent response actions are important concerns and are examined more fully in the next section for a more select set of critical pre-crash scenarios where their interactions and complexities can be resolved by video analysis.

Figure 3-99 shows the rate of occurrence of the pre-crash scenarios on freeways as a function of cruise control mode. The relative pattern among the modes is consistent across all the scenarios. That is, for each scenario type, the rate is highest for manual driving, lowest for CCC driving and in between for ICC driving. If collisions were proportional to the pre-crash scenario rate, there would be significantly fewer rear-end collisions with ICC driving compared to manual driving for each pre-crash scenario type. As mentioned above, the four pre-crash scenarios listed here are the dominant pre-crash scenarios associated with rear end collisions.

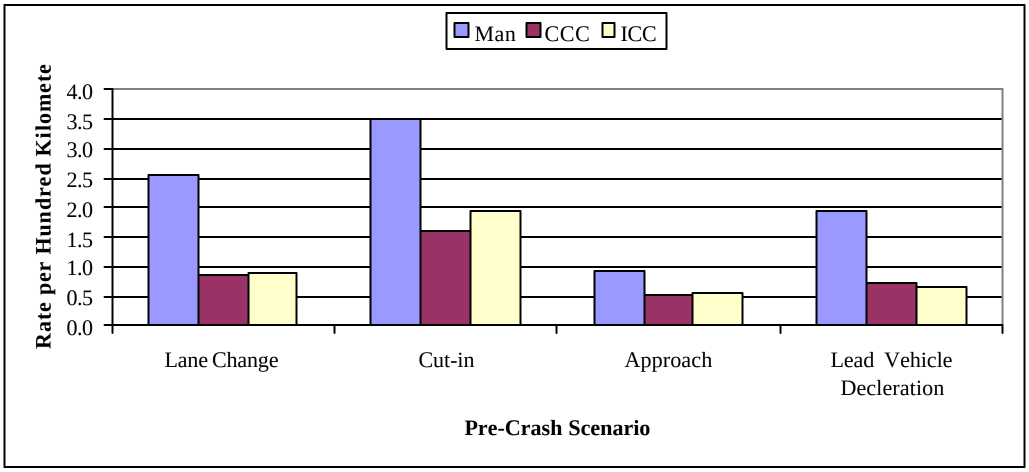

Figure 3-99 Average Rate of Occurrence of Pre-Crash Scenario as a Function of Cruise Control Mode - Freeways

The **cut-in pre-crash scenarios** were the most frequent and occurred at a rate of 3.5 per hundred kilometers for manual, 1.9 per hundred kilometers for ICC and 1.6 per hundred kilometers for CCC. The **approach pre-crash scenarios** occurred least frequently, at a rate of 0.9 per hundred kilometers for manual, and 0.5 per hundred kilometers for ICC and CCC.

The differences between manual, CCC, and ICC are largely consistent with the finding that manual mode was used more during heavy traffic and congestion, while CCC was used more during light traffic. The differences between ICC and CCC were not substantial. The largest difference, albeit a small one, was for the **cut-in pre-crash scenario**. The difference between ICC and manual for all pre-crash scenarios was relatively large.

Summary Observations Regarding ICC Influence on Occurrence of Pre-Crash Scenarios – Freeways To the extent that the rate of these pre-crash scenarios scenarios are proportional to the rate of occurrence of rear end collisions the results from Figure 3-99 suggest a strong potential safety effect for ICC relative to manual driving. While ICC and CCC rates are about equal, the functional capabilities of the ICC system to automatically resolve the pre-crash situation may also make ICC more safety beneficial compared to CCC.

With pre-crash scenario rates increasingly available in national collision databases, and with pre-crash scenario rates also available from field operational tests, including that for normal manual driving, using the methodology developed in this study, it may be eventually possible to link the two to provide a more reliable and accurate estimation of collision risk associated with ITS devices.

3.9.2.2 Driving Behavior During Critical Pre-Crash Scenarios. To further explore the relationship between cruise mode and the pre-crash scenarios, the video episode data collected during the FOT were examined (as was done above for the close call analysis). First, for each driver the captured video episodes were searched, and the cases with the highest observed braking and the highest required braking force (near encounter videos) were selected for analysis in this section. For videos captured because the brake force criterion (-0.05 g) was exceeded, the highest observed braking force was the selection criterion for the cases to be included in the analysis. For videos captured because the near encounter criterion was exceeded (< -0.05 g required to avoid coming within 0.3 s time-headway) the maximum required braking force was the criterion for the cases to be included in the analysis. For these latter cases, the drivers of the host vehicles may still have braked during the episodes, but the observed (actual) braking forces, if any, would be less than the required braking force as determined by the near encounter algorithm. (A comparison of the observed braking distributions versus the required braking distributions for the near encounter events is given in Appendix L.)

3.9.2.2.1 Braking Events. The distributions for the braking events for which video data were available are shown in Figure 3-100. The distributions apply to all roadways with velocities greater than 64.4 km/h, with and without a preceding vehicle. Figure 3-101 shows a similar distribution for situations with a preceding vehicle. The differences between the distributions are minor. Most of the braking levels were below 0.3g. There were only 56 events with braking levels above 0.3g. As shown in Figure 3-102, most of the higher braking levels with a preceding vehicle present tended to occur on arterials for all modes or on exit ramps of freeways for the manual mode. Although not shown in the figure, the videos revealed that higher brakings also tended to occur in heavier traffic. Mileage by road type for all driving is not available to normalize these results.

When normalized by test mode mileage the number of video braking events greater than 0.05 g per kilometer with a lead vehicle present was the same for ICC and CCC driving (0.026), and substantially more for manual driving (0.060). The number of braking events above 0.25 g per kilometer with a lead vehicle present was distributed as follows: ICC-0.0014, CCC-0.0006, Manual-0.0029. Thus, in both cases the ICC braking levels were substantially less than that for manual driving. It should also be noted that the CCC braking levels were less than that for ICC driving when braking levels above 0.25 g were considered. These braking event results do not take into account the driving scenario or roadway type.

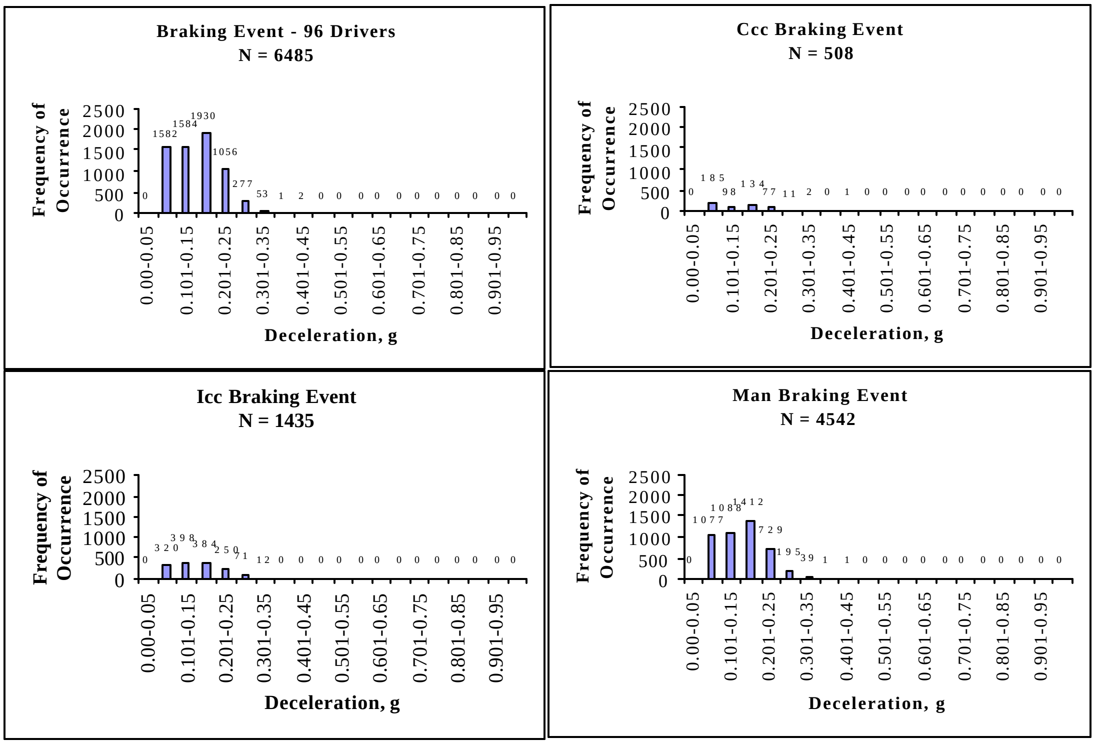

Figure 3-100 Distribution of Braking Events Above 0.05g Captured on Video Episodes, Velocities Greater Than 64.4 km/h, With and Without Preceding Vehicle - All Roadways

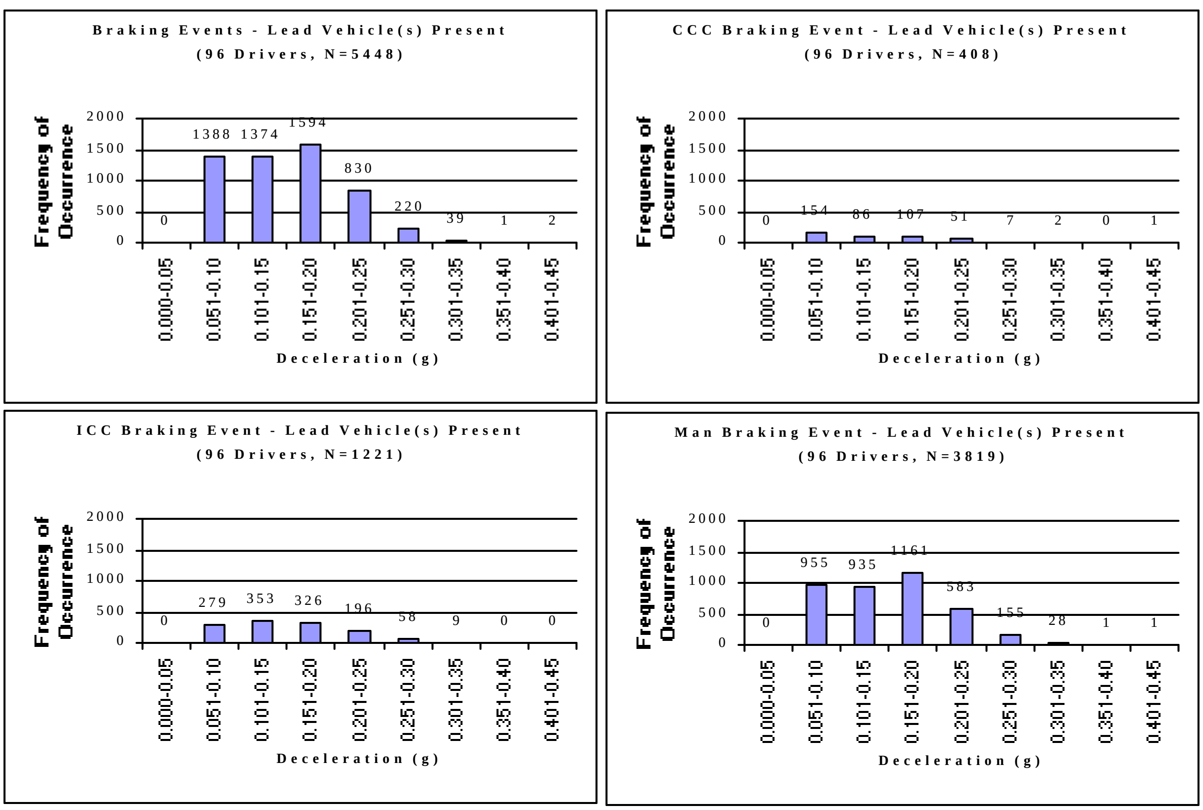

Figure 3-101 Distribution of Braking Events Above 0.05g Captured on Video Episodes, Velocities Greater Than 64.4 km/h, With Preceding Vehicle-All Roadways

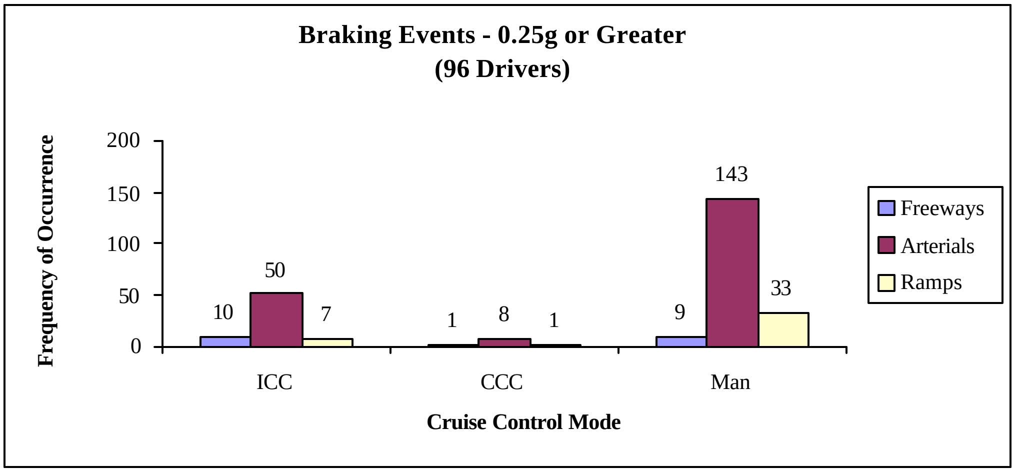

Figure 3-102 Distribution Braking Events by Cruise Control Mode and Road Type

3.9.2.2.2 Near Encounter Events. The distributions for the near encounter events are shown in Figure 3-103. The distributions apply to all roadways with velocities greater than 64.4 km/h, and with a preceding vehicle. As indicated in Appendix L, the near encounter events tended to occur on freeways, and in many cases were not followed by actual braking but rather by a lane change of either the lead vehicle or the host vehicle at the end of the scenario. When normalized by test mode mileage, the number of video

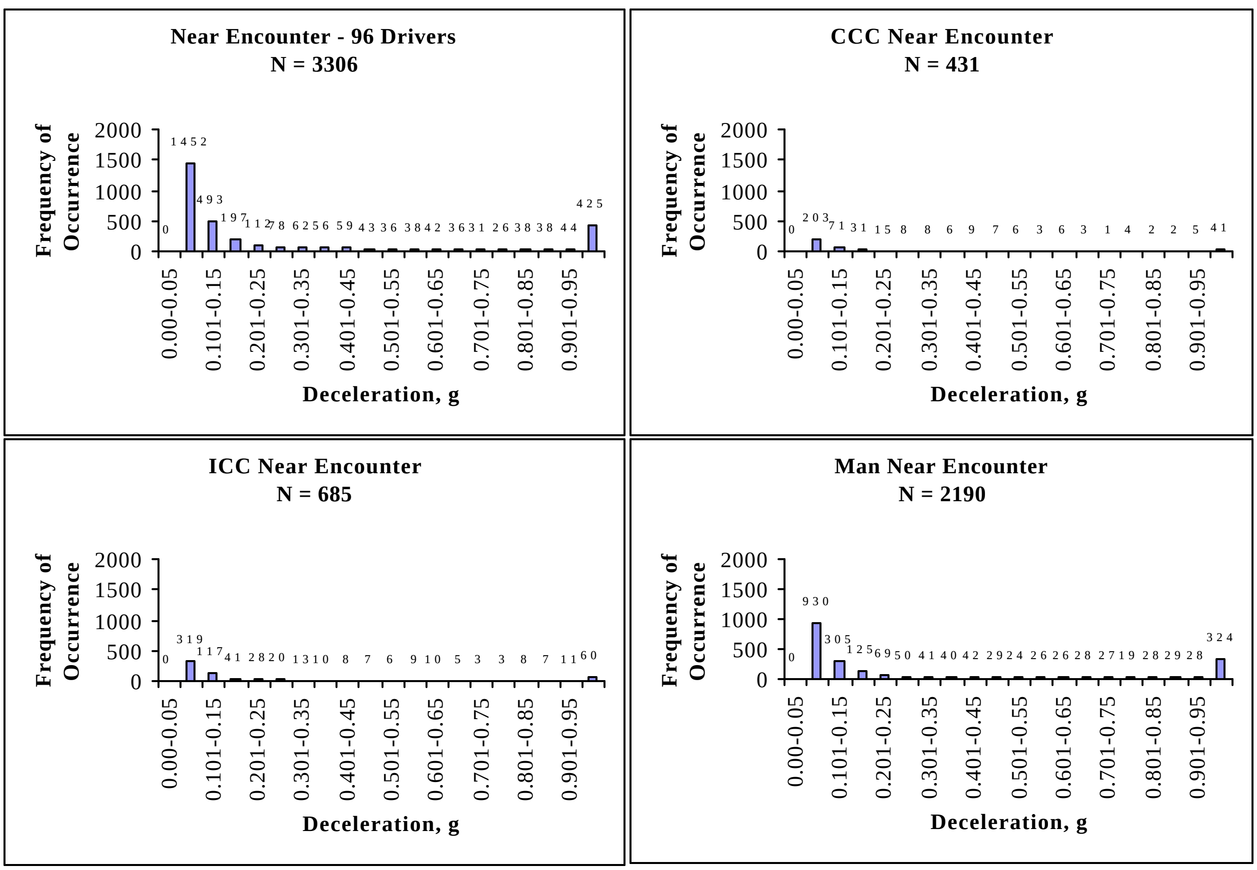

Figure 3-103 Distribution of Near Encounters Above 0.05g Captured on Video Episodes, Velocities Greater Than 64.4 km/h, With Preceding Vehicle - All Roadways

near encounter events per kilometer requiring a braking level of 0.05 g or greater to bring the host vehicle to within 0.3 second of the lead vehicle was substantially less for ICC driving (0.015) compared to CCC driving (0.028) and manual driving (0.034). The number of near encounter events per kilometer requiring a braking level of 0.25 g or greater to bring the host vehicle to within 0.3 second of the lead vehicle – which the algorithm also captured - was distributed as follows: ICC-0.0038, CCC-0.0071, Manual-0.0120. Thus, in both cases the ICC near encounter levels were substantially less than that for both CCC driving and manual driving. These near encounter event results also do not take into account the driving scenario or roadway type.

3.9.2.2.3 Critical Pre-Crash Scenarios on Freeways. In this section, critical scenarios are defined as the highest braking or near encounter events for each driver. (See Appendix L for the definition and determination of these scenarios.) Furthermore, at the time the video was triggered there had to be a lead vehicle present in the video and that lead vehicle had to come within 30.5 meters of the host vehicle during the scenario. Using this methodology, a total of 41 videos were identified that were captured during freeway driving. These videos came from 29 drivers. The methodology and the resulting analysis produced 2 *lane change* cases, 14 *cut-in* cases, 12 *approach* cases, and 13 *lead vehicle decelerates* cases for a total of 41 cases. Note that in this section the *lead vehicle deceleration* cases are not based on a minimum level of 0.25g as in Section 3.9.2.1 but rather include a range of levels as determined from the video analysis. Using the methodology described in Appendix L, only 2 of the 13 *lead vehicle deceleration* cases involved situations where the lead vehicle decelerated greater than 0.25g.

The key points for each scenario type are discussed next.

Lane Change: There were no instances of manual driving represented in this sample. Both cases began with velocities between 104 and 109 km/h. Both the ICC and CCC cases lie relatively close to state space boundary 3, but were outside that boundary at the beginning of the episodes. The CCC episode lasted 10 seconds and resulted in the shortest minimum headway, 7.6 meters. The ICC episode lasted 4 seconds and had a minimum headway of 13.7 meters. Both cases were resolved without braking greater than 0.1 g. Neither case appears to raise particular safety concerns.

Cut-in: *Cut-ins* were the second most represented pre-crash scenarios in this sample, and ICC cases were involved in all but three of the sample cases. Perhaps because it provides longer headways, the ICC system also provides other drivers more opportunities to cut in front of ICC users. Figure 3-104 shows a summary of the pre-crash video analysis results for the *cut-in* pre-crash scenarios. The number of drivers contributing to each data point is shown aside the legend for each mode. The results are expressed in terms of the mean initial range rate (Rdoti), initial range (Ri), minimum range (Rm), and braking level (Br), and the percent of cases that resulted in a lane change maneuver at the end of the scenario to avoid a collision (Lc). The values of the variables are shown with each variable and for each mode.

These scenarios were short, averaging about 8 seconds. The minimum ranges tended to be substantially shorter for ICC driving although the initial ranges also tended to be somewhat shorter. The minimum ranges still left an acceptable safety margin especially considering that the braking forces used never exceeded 0.21 g, and for all the ICC cases never exceeded 0.14 g. Both of these braking levels occurred at velocities greater than 114 km/h. Only one of the cases, for manual driving, ended in a lane change by the host vehicle driver. Again, these data do not appear to raise safety concerns. Nor is there sufficient data here to suggest a safety benefit resulting from the use of ICC.

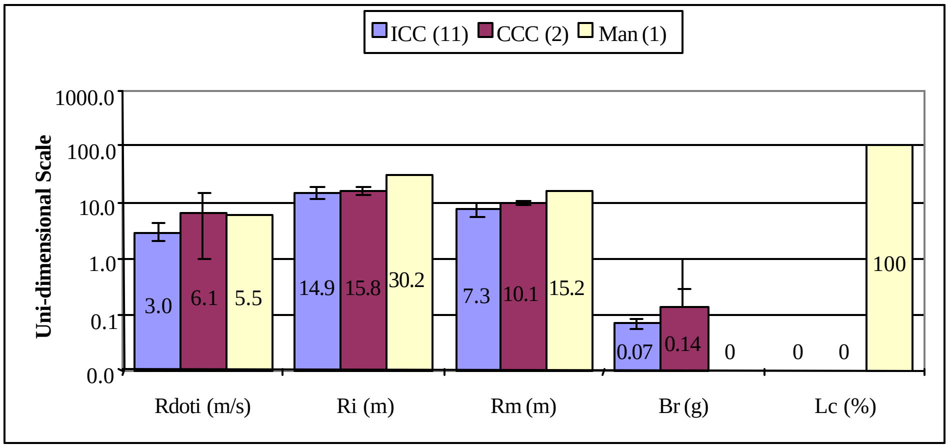

Figure 104 Summary of the Video Analysis Results for the *Cut-In* Pre-Crash Scenario as a Function of Cruise Control Mode

Approach*:* Figure 3-105 shows a summary of the pre-crash video analysis results for the *approach* pre-crash scenarios.

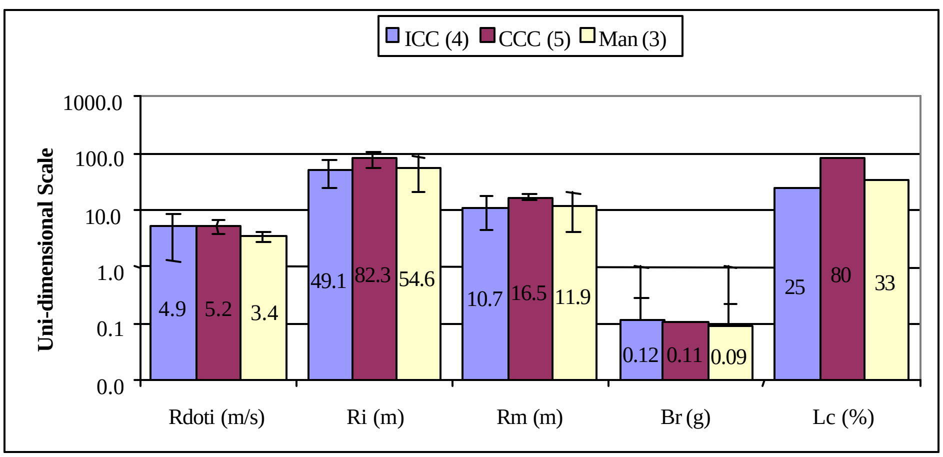

Figure 3-105 Summary of the Video Analysis Results for the *Approach* Pre-Crash Scenario as a Function of Cruise Control Mode

Figure 3-105 shows that the initial conditions for the *approach* scenarios were not particularly severe. The mean initial ranges were greater than 49 meters while the mean initial range rates were less than 5 m/s. Although not shown in the figure, initial velocities ranged between 93 and 115 km/h, and the duration of the scenario ranged from 13 to 22 seconds. The minimum ranges for ICC driving tended to be slightly lower than those for manual driving, and substantially lower than those for CCC driving. (The shortest minimum range was actually for manual driving.) Part of the explanation for the difference in minimum ranges is in the different levels of initial conditions between the modes. The mean initial ranges, for example, tended to be lower for ICC driving.

ICC driving tended to produce slightly harder actual brakings compared to both manual driving and CCC driving. There was one ICC case where the braking level reached 0.3g. For the remaining cases, the braking levels did not exceed 0.15 g. All the higher braking levels occurred at relatively high velocities, i.e., greater than 96 km/h. Figure 3-105 indicates that one out of 4 of the ICC cases, 4 out of the 5 CCC cases, and one out of the 3 manual cases ended in a lane change by the host driver. There were not sufficient data on response times for these scenarios to make a meaningful comparison. In most cases there was no clear stimuli as would be expected for this scenario. The *approach* videos did not suggest that ICC presented either a particular safety hazard or a particular safety benefit.

Lead Vehicle Deceleration: Figure 3-106 shows a summary of the pre-crash video analysis results for the *lead vehicle deceleration* pre-crash scenarios. The duration of these cases ranged from 6 to 22 seconds. The highest lead vehicle decelerations observed were 0.48 g for a CCC case, and 0.41 g for an ICC case. ICC driving tended to produce substantially harder brakings compared to both manual driving and CCC driving. However, ICC driving tended to encounter lead vehicles at substantially longer initial ranges. The minimum ranges were well within acceptable margins. Although ICC and CCC examples had the highest observed braking forces, it was the manual cases that appeared most severe when the range range-rate space is considered. Once again, all the higher braking levels occurred at relatively high velocities. The observed braking level for the CCC case where the lead vehicle decelerated at 0.48 g was 0.43 g and occurred at 82 km/h. The observed braking level for the ICC case where the lead vehicle decelerated at 0.41 g was 0.30 g and occurred at 109 km/h. All the other higher braking levels occurred at velocities greater than 93 km/h.

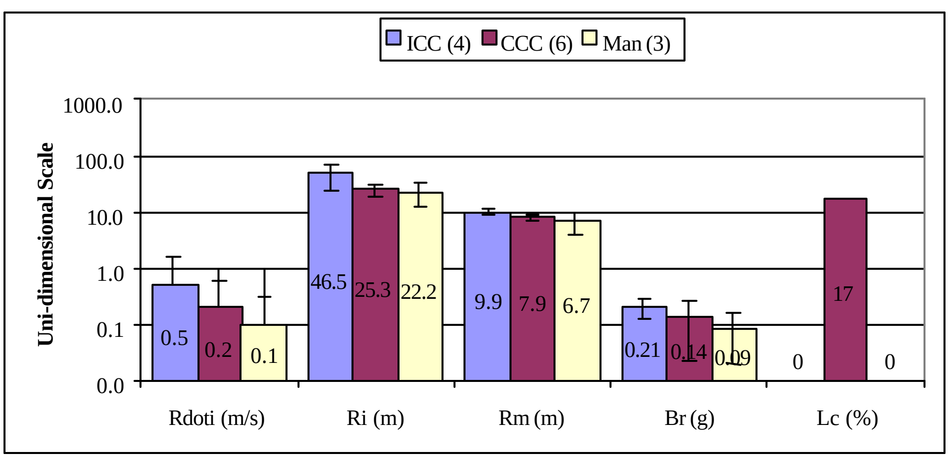

Figure 106 Summary of the Video Analysis Results for the *Lead Vehicle Deceleration* Pre-Crash Scenario as a Function of Cruise Control Mode

Only one case, for CCC (out of six cases), ended in a lane change by the host vehicle driver. Regarding response times, there were more cases with distinct response times for this scenario (5) compared to the *approach* scenario (1), but still not a sufficient amount for a meaningful comparison. Part of the explanation for the lack of response times may be that nine of the cases had a lead vehicle decelerating at a level of 0.08 g or less, perhaps not large enough to provide a distinct stimulus or prompt a distinct response.

3.9.2.2.4 Critical Pre-Crash Scenario Summary. The pre-crash scenarios together with a prioritization by critical cases provided an orderly and efficient means for examining video episodes and better understanding the effect that ICC has on driving safety. The analysis showed a higher rate of occurrence of critical pre-crash scenarios for ICC driving compared to manual driving, and when they occur, a slight tendency towards higher braking levels, and lower minimum headways. Although the results are not statistically significant, they do present a safety concern. This finding seems to indicate that drivers tend to wait to see if the ICC system would resolve the situation developing during the scenarios. For those cases not resolved by the ICC, the driver eventually decides to intervene and brake. Consequently the braking levels are somewhat higher, and minimum headways somewhat shorter than would have normally been the case had the driver been driving in the manual mode. There are of course safety implications with these findings. But another implication is that drivers may be learning about the system and, as they become more familiar with its operation under these conditions, their pattern of driving with ICC could be expected to change to match their driving pattern without ICC.

Appendix L contains a more complete discussion of the critical pre-crash scenario video analysis. Results for arterials and ramps are covered in addition to freeways.

3.10 Driver Perceptions of the Safety of the ICC System

The post-test questionnaire included an item that asked drivers to rank the three cruise modes (manual, CCC and ICC) with respect to safety. Each driver was to rank one of the modes most safe (1), one of the modes second safest (2), and one of the modes third safest (3). The mean ranks that resulted are shown in Table 3-55 as a function of age group and previous cruise usage. Overall, drivers ranked manual driving most safe, and CCC least safe, with ICC intermediate. The differences between rankings were statistically reliable, by Friedman's Rank test, $\chi^2(2) = 88.6$, $p < 0.001$. The only deviation from the overall trend was among older drivers who were not previous cruise control users. Among this group, there was no significant difference among the three modes ranks of ($p > 0.10$).

Table 3-55 Participants' Mean Rank of the Three Cruise Control Modes with Respect to Safety (1 indicates most safe)

Age Group	*Mode*	*Nonuser*	*User*	*Overall*
20-30	**Manual**	1.1	1.3	1.3
	CCC	2.8	2.7	2.7
	ICC	2.1	2.0	2.0
40-50	**Manual**	1.0	1.4	1.2
	CCC	2.8	2.7	2.8
	ICC	2.2	1.9	2.0
60-70	**Manual**	1.3	1.9	1.7
	CCC	2.6	2.3	2.4
	ICC	2.1	1.8	1.9
Overall	**Manual**	1.1	1.5	1.4
	CCC	2.7	2.6	2.6
	ICC	2.1	1.9	2.0

Interestingly, when ranking the modes 1st, 2nd, and 3rd as to which they drove most cautiously, drivers indicated that they drove most cautiously with ICC and least cautiously in manual. The mean ranks that resulted are shown in Table 3-56. Again the differences in mean rankings were statistically reliable $\chi^2(2) = 12.6$, $p < 0.01$. Whether drivers felt that ICC required more caution, or enabled them to be more cautious, was not clear from the questionnaire responses. However, in the focus group discussions, there were no indications that ICC required particular caution, and there were indications that drivers found ICC to be relaxing.

Table 3-56 Mean Ranking of Cruise Control Modes with Respect to "Under which mode…do you drive most cautiously"

Mode	*Mean Rank*
Manual	2.2
CCC	2.1
ICC	1.7

Drivers were asked whether they agreed with the question "Do you think [ICC] is going to increase driving safety?" Responses were on a scale from 1 to 7 where 1 indicated strong disagreement and 7 indicated strong agreement. The mean response was 5.28, standard error, 0.14, and there were no significant age group or previous cruise usage differences. Thus it appears that drivers agreed that they think ICC would increase safety.

Drivers indicated that they felt safe using the ICC system. On a scale from one to seven, where one indicated feeling “very unsafe”, and seven indicated feeling “very safe”, the mean response was 5.93, standard error 0.11.

In a final safety related questionnaire item, drivers were asked if they ever came close to having a crash because they were using the ICC system. Of the 101 drivers who responded to this question 98 said no, and 3 said yes. Of the three who said the system nearly caused a crash, one attributed the situation to inexperience using the system. The incident this driver referred to occurred on the first day that the system was active.

Another driver who said yes indicated that the car ahead was going too slow, and the system’s deceleration was not enough. This driver apparently regarded this system to be unsafe because it could not compensate, without driver intervention, for all closing situations.

The third driver, who attributed a near crash to ICC use, described an incident in which the driver behind the ICC vehicle was tailgating. When the ICC system then slowed in response to a slower preceding vehicle, the tailgater nearly hit the ICC vehicle. This ICC respondent apparently believed that the ICC system was responding sooner than the tailgater should have expected.

Drivers’ Perception of Safety Summary. Overall, the users’ perception of the safety of the ICC system was positive. They indicated that they drove more cautiously with ICC, they believed that ICC was going to increase driving safety, and they felt safe using the ICC system.

3.11 Widespread Safety Effects

The evaluation discussed in previous sections focussed on determining whether ICC may increase or decrease crash risk to the equipped vehicle relative to driving manually or with conventional cruise control. In this section, based on the field data, estimates are made of the widespread effects of fully deployed ICC-like systems on the frequency of rear-end collisions. The focus here is on freeways where most of the driving mileage above 40 km/h on roads in Southeastern Michigan (54 percent), and highest percentage of ICC usage (62 percent) occurred.

The analysis was based on a methodology developed and applied by the National Highway Traffic Safety Administration (NHTSA) to assess the safety benefits of new prototype, advanced-technology collision avoidance systems. NHTSA’s methodology for appraising the national safety benefits of such systems is founded on estimation of the effectiveness of a system to eliminate or ameliorate collisions in driving situations characterized in national crash databases (Burgett, 1995). The estimated effectiveness is then applied to data from national crash databases to estimate the number and severity of collisions that would have been eliminated were the system been in place when crash data were collected. The NHTSA methodology was used previously to provide preliminary estimates of the safety benefits of collision avoidance systems that address rear-end, lane change, and single vehicle roadway departure crashes (NHTSA, 1996; Najm and Burgett, 1997). That study was a first attempt to assess and quantify the safety benefits of advanced-technology crash countermeasure systems using experimental data obtained from limited driving tests on public roads and in driving simulators *with* and *without* the assistance of a collision avoidance system. Of particular interest with respect to this ICC safety evaluation, the safety benefits were estimated for the precursor to the current ICC system. The data for that early ICC test was obtained from 36 drivers who traversed an 89-kilometer highway route under close supervision (NHTSA, 1996).

The widespread impact evaluation reported here extends the previous ICC evaluation in several ways:

- the field data covered a much wider variety of freeway environments,
- the number of drivers observed was increased from 38 to 106 (for 2 drivers, freeway data were not available),
- the data were obtained in a more natural setting,
- fewer assumptions were required in performing the analysis, and
- the focus was on two distinct rear-end pre-crash scenarios.

3.11.1 Widespread Safety Benefits Assessment Methodology

Because the ICC system adjusted the gap between the host vehicle and a preceding vehicle, and collected detailed data on the dynamics of car-following, rear-end collisions were selected as the focus of the widespread safety benefits analysis. To avoid the problem of distinguishing roadway features, such as overpasses, from vehicles, the ICC system was designed to not respond to stopped or slow-moving objects. Thus, the impact analysis examined only the cases where the preceding vehicle was moving, and does not apply to rear-end collisions with stopped vehicles.

The number of rear-end collisions that might be avoided with the use of the ICC system, *B*, was estimated by:

$$B = SE \times N_{wo}$$

where:

SE	=	Total ICC system effectiveness in all relevant rear-end pre-crash scenarios.
N_{wo}	=	Number of relevant rear-end collisions without ICC system intervention.

The total ICC system effectiveness was calculated as:

$$SE = \sum_{i=1}^{2}\left(\sum_{j=1}^{8} E(i,j) \times P(i,j) \times u_{ICC}(j)\right) \times F(i)$$

where:

i = Index to two rear-end pre-crash scenarios addressed by the ICC system.

j = Index to eight following-vehicle velocity-bins.

$E(i,j)$ = Absolute effectiveness of a driver using the ICC system in preventing a rear-end collision in pre-crash scenario i within velocity bin j.

$P(i,j)$ = Probability that a relevant rear-end collision will be of pre-crash scenario i within velocity bin j.

$u_{ICC}(j)$ = Proportion of time the ICC system was engaged within velocity bin j.

$F(i)$ = Fraction of relevant rear-end collisions in pre-crash scenario i relative to the relevant rear-end crash size.

This analysis assesses the safety benefits of the ICC system in two rear-end pre-crash scenarios that were distinguished by whether the lead vehicle either suddenly decelerated in front of the following vehicle, or was traveling at a constant lower velocity when encountered by the following vehicle. In both pre-crash scenarios, the following vehicle was assumed to be initially traveling at a constant velocity. Moreover, the driver of the following vehicle was assumed to apply emergency braking in response to sudden deceleration, or the constant lower velocity of the lead vehicle. To better equate traffic conditions across cruise modes, the analysis estimated the effectiveness of the ICC system in eight travel velocity bins. These travel velocity bins were: 40 - 56, 56 - 73, 73 - 89, 89 - 97, 97 - 105, 105 - 113, 113 - 121, and ≥ 121 km/h.

The General Estimates System (GES) crash database was queried to obtain values for $P(i,j)$ and $F(i)$. The ICC FOT database provided values for $u_{ICC}(j)$. Values for $E(i,j)$ were estimated using computer simulations. The parameter $E(i,j)$ is mathematically expressed as:

$$E(i, j) = 1 - \frac{p_w(i, j)}{p_{wo}(i, j)}$$

where $p_w(i,j)$ and $p_{wo}(i,j)$ denote the probabilities of a rear-end collision in pre-crash scenario i within velocity bin j <u>*with*</u> and <u>*without*</u> the ICC system, respectively. To obtain an estimate for the total ICC system effectiveness, *SE*, Monte Carlo computer simulations generated a total of thirty-two estimates of these probabilities using data from the ICC FOT. Monte Carlo simulation is appropriate for obtaining estimates of the crash probability where a model of the driving environment under study is available, and sufficient data are available to estimate parameters in the model. Models of the two rear-end pre-crash scenarios were simulated using kinematic representations of vehicle movements, and simple time delays of driver braking response and vehicle braking. The models determined if a rear-end collision occurred in each of the two scenarios for some given initial conditions. In this analysis, a collision was counted only if the relative speed at impact between the following and lead vehicles was over 8 km/h. Field test data on following vehicle speed, range, range-rate, following vehicle deceleration, and driver braking response time were used as inputs to the simulations. The field test data were augmented by vehicle emergency braking-level data already gathered from controlled experiments, not part of the field test.

To provide an indication of the contribution of the headway adjustment feature of the ICC system to the safety benefit, the total system effectiveness of CCC was also evaluated. Additional sixteen values of $p_W(i,j)$ were estimated for CCC using Monte Carlo simulations. The analyses adopted the simplifying assumption that the market penetration of both the ICC and CCC systems in the vehicle fleet was 100 percent. That is, for any given simulation, the following vehicle was always equipped with the cruise mode being considered - whether the system was turned on was based on the participants usage rates, also from the field test data.

3.11.2 Rear-End Crash Statistics

The rear-end crash type encompasses multi-vehicle collisions that occur when the front of a following vehicle strikes the rear of a lead vehicle, both traveling in the same lane. According to 1996 GES crash database, rear-end collisions accounted for about 26.5 percent of all police-reported collisions in the United States, or approximately 1.816 million collisions. Of these rear-end collisions, about 8.5 percent, or 154 thousand police-reported collisions occurred on interstate highways. Table 3-57 lists the relative frequency of three pre-crash scenarios that happened immediately prior to these rear-end collisions. These scenarios are solely based on the dynamic state of the lead vehicle that preceded the collision and disregard the following vehicle dynamic state. The *Movement Prior to Critical Event* variable in the 1996 GES crash database was used to identify these scenarios (Najm, et al., 1998). This analysis excludes the pre-crash scenario where the lead vehicle was stopped, because the ICC system did not respond to stationary objects. This pre-crash scenario involving a stopped lead vehicle accounts for over one third of all rear-end collisions on interstate highways, and thus will be important to consider in evaluation of rear-end collision avoidance systems. The ICC system was evaluated only for its car following properties where the lead vehicle was moving.

Table 3-57 Definition and Relative Frequency of Rear-End Pre-crash Scenarios on Freeways (Based on 1996 GES)

No.	*Scenario Definition*	*Relative Frequency*
1	Lead vehicle suddenly decelerates in front of following vehicle.	42.9%
2	Lead vehicle was stopped in traffic lane when encountered by following vehicle.	36.3%
3	Lead vehicle was moving at constant, lower speed than following vehicle.	20.8%

Figure 3-107 shows the distribution of police-reported rear-end collisions for rear-end pre-crash scenarios 1 and 3, on freeways, arranged by the travel velocity of the following vehicle. Crash statistics on travel velocity of the following vehicle were obtained from the *Travel Speed* variable in the GES crash database. *Travel Speed* indicates the travel velocity of the following vehicle before the driver's realization of the impending danger. It should be noted that about 60 percent of the actual velocity data in the 1995 and 1996 GES crash databases were coded as "unknown". In rear-end pre-crash scenario 1, where the lead vehicle suddenly decelerates on freeways, about 84 percent of police-reported rear-end collisions involved a traveling velocity below 89 km/h. In a similar travel velocity range, about 51 percent of police-reported rear-end collisions occurred in rear-end pre-crash scenario 3, where the lead vehicle was traveling at a constant velocity lower than the following vehicle. A recent analysis of most frequent rear-end pre-crash scenarios has shown that a significant majority of police-reported rear-end collisions occurred below the posted speed limit. The latter finding may indicate that traffic was congested at the time of the crash (Wiacek and Najm, 1999).

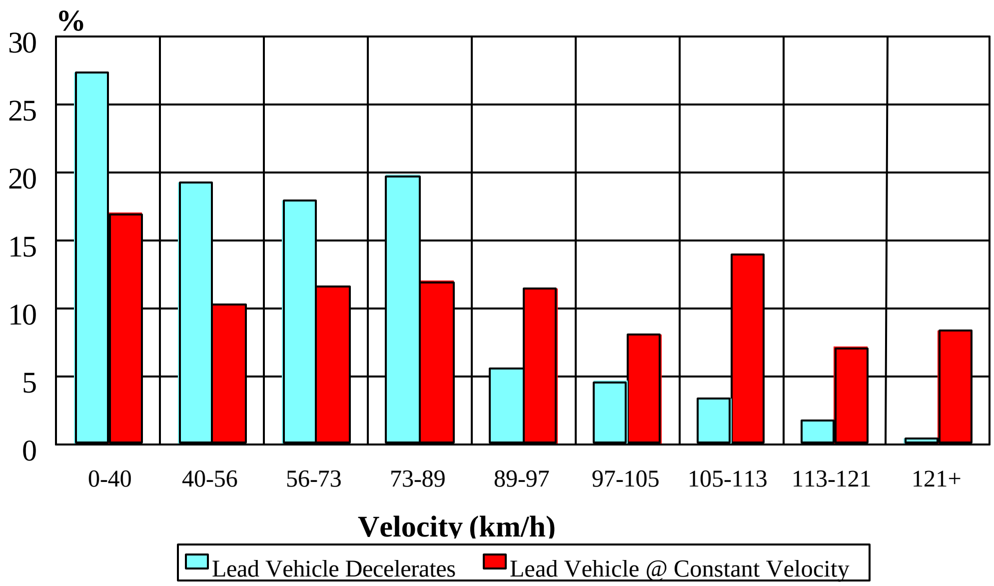

Figure 3-107 Distribution of Police-Reported Rear-End Collisions by Following Vehicle Travel Velocity for Two Pre-Crash Scenarios on Freeways (Based on 1995-1996 GES)

This analysis does not consider police-reported rear-end collisions that involved travel velocities below 40 km/h because the ICC system did not operate below this velocity. About 27 percent and 17 percent of police-reported rear-end collisions on freeways fall below this velocity for pre-crash scenarios 1 and 3, respectively. Thus, the number of relevant rear-end collisions on freeways targeted by the ICC system, N_{wo}, was estimated at about 75 thousand police-reported collisions, as shown in Table 3-58. Consequently, the fractions of relevant police-reported rear-end collisions, *F(i)*, was 0.6421 for pre-crash scenario 1, and 0.3579 for scenario 3. Table 3-59 lists the probabilities that a relevant police-reported rear-end collision was of either pre-crash scenario within any of the eight velocity bins, *P(i,j)*.

Table 3-58 Size Derivation of Police-Reported Rear-End Collisions on Freeways Targeted by the ICC System (Based on 1996 GES)

Police-Reported Rear-End Collisions	*Frequency (thousands)*	*% of Total*
Total	1816	100
Freeways	154	8.5
Freeways, excluding lead vehicle stopped	98	5.4
Freeways, excluding lead vehicle stopped and travel velocities below 40 km/h	75	4.1

Table 3-59 Probabilities of Pre-Crash Scenarios Per Travel Velocity Bin (km/h) for Rear-End Collisions on Freeways (Based on 1995-1996 GES)

Scenairo	*40 - 56*	*56 - 73*	*73 - 89*	*89 - 97*	*97 - 105*	*105 - 113*	*113 - 121*	*≥121*
1	0.2651	0.2463	0.2735	0.0772	0.0626	0.0459	0.0230	0.0063
3	0.1236	0.1386	0.1461	0.1386	0.0974	0.1685	0.0861	0.1011

3.11.3 Inputs to Simulation

Inputs to the simulation models consisted primarily of data from the FOT, which included:

- proportion of time ICC or CCC system was engaged on freeways in the presence of a valid lead vehicle target for each of the eight travel velocity bins,
- following vehicle speed on freeways in the presence of a valid lead vehicle target for each of the eight travel velocity bins,
- range between following and lead vehicles on freeways for each of the eight travel velocity bins,
- range-rate between following and lead vehicles on freeways for each of the eight travel velocity bins,
- ICC-equipped vehicle deceleration generated by brake presses in the manual mode on freeways for each of the eight travel velocity bins, which was utilized to describe the lead vehicle deceleration parameter in the rear-end pre-crash scenario 1 model, and
- braking response time of drivers in the following vehicle when reacting to lead vehicle brake lights on freeways.

The above data were supplemented by vehicle emergency deceleration data, which were obtained from the literature.

This analysis did not adopt the driver as "the primary unit of analysis" as was done in the other analyses discussed in previous sections. This difference in approach was necessary because of insufficient quantities of FOT data that were available to conduct Monte Carlo simulations for each driver. Such an approach would require a large quantity of FOT data to be accumulated by each driver in order to supply forty-eight analysis cells (i.e., 2 pre-crash scenarios × 8 travel velocity bins × 3 control modes). Thus, a total of 5,088 Monte Carlo simulations would be needed to account for all 106 FOT drivers who produced freeway data. Instead, FOT data from all drivers were aggregated and distributed among forty-eight cells for Monte Carlo simulations. As a result, this analysis does not give equal weight to all drivers, but rather weighs each driver by the amount of mileage driven on freeways above 40 km/h in Southeastern Michigan.

System Usage. The proportions of time the ICC and CCC systems were engaged by the test drivers on freeways, while following a lead vehicle, are shown for each of the eight travel velocity bins in Table 3-60. The CCC system usage data were obtained from the first week of driving during the FOT. The ICC system usage data were derived from the second and later weeks of driving. As seen in Table 3-60, the ICC system was engaged more often than the CCC system in each of the eight travel velocity bins.

Table 3-60 Proportions of Time ICC and CCC Systems Were Engaged on Freeways behind a Valid Lead Vehicle as a Function of Travel Velocity (km/h)

	40 - 56	*56 - 73*	*73 - 89*	*89 – 97*	*97 - 105*	*105 - 113*	*113 - 121*	*≥121*
$u_{ICC}(j)$	0.0114	0.0620	0.2477	0.4945	0.6481	0.6961	0.6823	0.5891
$u_{CCC}(j)$	0.0003	0.0110	0.0519	0.1490	0.3265	0.4367	0.4142	0.2649

Velocity, Range, and Range-Rate. Data triads of vehicle velocity, range, and range-rate were sampled directly from the ICC field operational test data. The data for manual and CCC controls were collected during the first week of driving conducted by the test drivers. Data for ICC control were gathered from the second and later weeks of driving. The ICC driving data included all ICC settings: 1.0, 1.4, and 2.0 second time-headway settings. The data triads were sampled from the database, without regard to driver, trip, or headway setting, to preserve the interdependency among the velocity, range, and range-rate variables.

The relationships between range and range-rate at travel velocities between 105 and 113 km/h are illustrated in Figures 3-108 through 3-110 for manual, CCC, and ICC modes respectively. In manual mode, drivers kept shorter distances to lead vehicles ahead than in the other two cruise modes. Figure 3-109 shows that drivers in the CCC mode maintained longer ranges to lead vehicles ahead than in the manual mode and exhibited higher relative speeds than in the other two cruise modes. The control actions of the ICC system are manifested by the three peaks shown in Figure 3-110, which roughly reflect the 1.0, 1.4, and 2.0 second time-headway settings of the system.

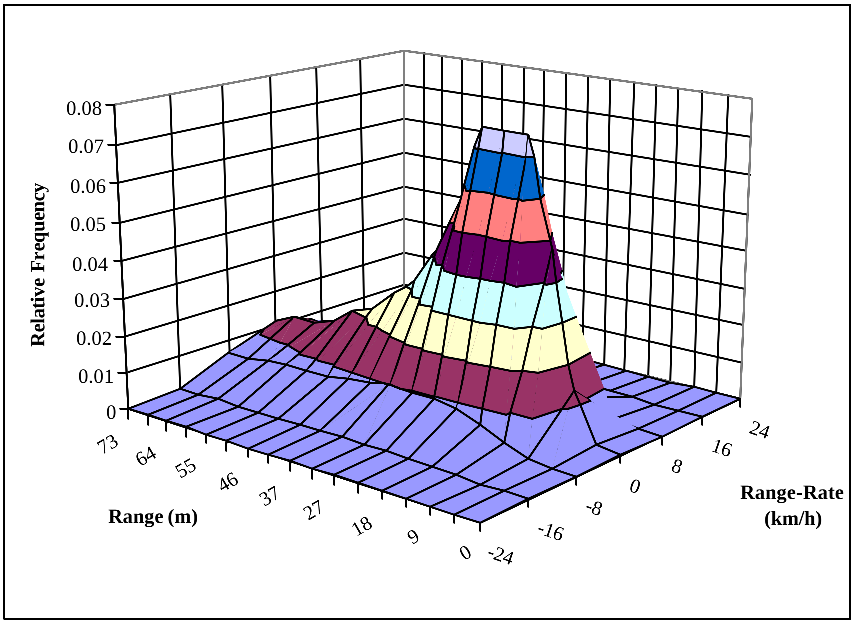

Figure 3-108 Range versus Range-Rate Plot for Manual Driving between 105-113 km/h on Interstates

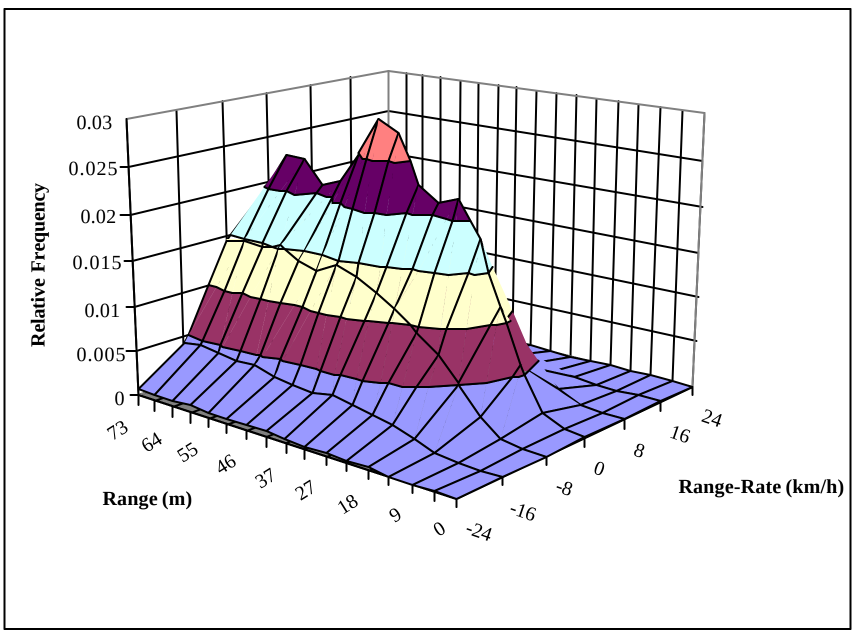

Figure 3-109 Range versus Range-Rate Plot for CCC Driving between 105-113 km/h on Freeways

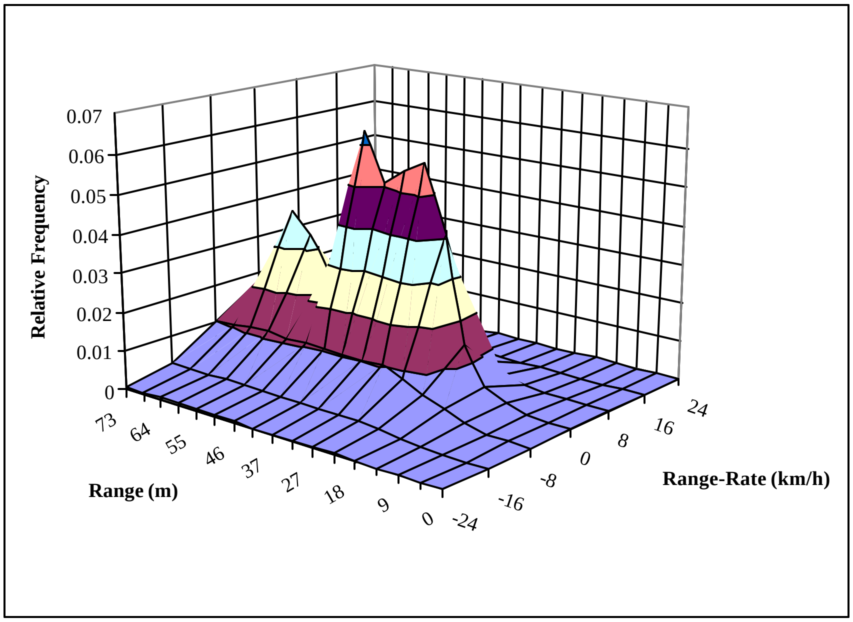

Figure 3-110 Range versus Range-Rate Plot for ICC Driving between 105-113 km/h on Freeways

Lead Vehicle Deceleration. The lead vehicle deceleration is a parameter of the rear-end pre-crash scenario 1 model that represents a lead vehicle suddenly decelerating in front of a following vehicle. The sudden deceleration of the lead vehicle results from vehicle brake actuation. This parameter was described in the simulations using the deceleration levels exhibited by the ICC-equipped vehicle in the ICC field operational test while traveling in the manual control mode on freeways. The use of the ICC-equipped vehicle deceleration data was preferred over the lead vehicle deceleration data because brake-only deceleration data of the equipped vehicle were easily identified in the ICC FOT database. Thus, the simulated deceleration levels were limited to observed decelerations resulting from brake pedal activation by the ICC-equipped vehicle during travel velocities over 40 km/h. Figure 3-111 shows a histogram of brake-only deceleration levels observed from the ICC-equipped vehicles driven manually on freeways for velocities over 40 km/h. These deceleration levels have an average of approximately 0.1g.

Driver Braking Response Time. Table 3-61 lists the statistics of driver braking response time as a function of time headway for manual, CCC, and ICC control modes on freeways. These statistics were derived from a sample of video data captured during freeway travel in the ICC FOT. A lognormal distribution was utilized to generate random numbers for the driver braking response time variable, bounded by minimum and maximum values shown in Table 3-61 (Taoka, 1989). This analysis correlates driver braking response time with time-headway, which is consistent with another experiment (Davis et al., 1990) that reported a decrease in driver braking response time as coupled vehicles drew closer together. It should be noted that driver braking response time in the CCC mode was assumed in this analysis to be similar to that for the ICC mode for a time-headway below 0.5 second on freeways, given that no video clips were available for the

CCC mode under this particular condition. In addition, driver braking response time was assumed to be the same in both rear-end pre-crash scenarios.

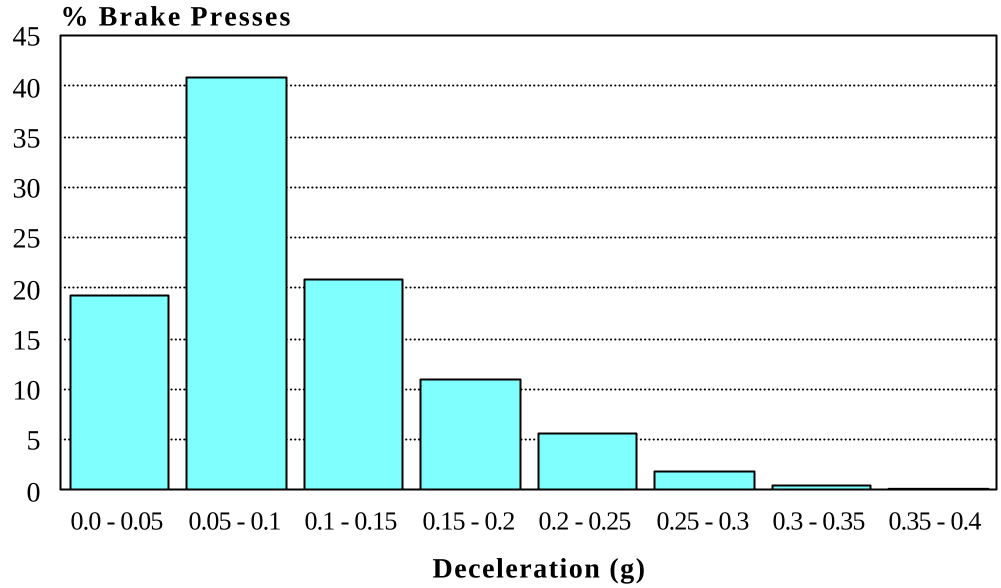

Figure 3-111 Histogram of Brake-Only Deceleration Levels Observed in Manual Driving on Freeways for Velocities over 40 km/h

Table 3-61 Statistics of Driver Braking Response Time versus Time-Headway

Mode\Time-Headway (sec)		*> 2.0*	*1.5 – 2.0*	*1.0 - 1.5*	*0.5 – 1.0*	*< 0.5*
Man	Mean (sec)	1.93	2.08	1.80	1.46	1.20
	Std Dev (sec)	1.03	1.13	1.03	0.89	0.84
	Max (sec)	4.61	4.62	4.50	4.51	3.62
	Min (sec)	0.33	0.11	0.11	0.11	0.11
CCC	Mean (sec)	2.50	2.66	2.34	1.67	1.25
	Std Dev (sec)	1.65	1.21	1.61	0.89	0.94
	Max (sec)	4.29	3.52	4.34	2.59	2.25
	Min (sec)	0.22	1.81	0.60	0.50	0.22
ICC	Mean (sec)	2.42	2.28	2.19	1.64	1.25
	Std Dev (sec)	1.35	1.24	1.11	1.05	0.94
	Max (sec)	4.84	4.29	4.01	4.72	2.25
	Min (sec)	0.93	0.22	0.60	0.22	0.22

Following Vehicle Deceleration. Monte Carlo simulations of both rear-end pre-crash scenarios assumed that the driver of the following vehicle would brake hard, at an emergency level, to avoid hitting the lead vehicle. The value of emergency deceleration ranges from about 0.5g to 0.75g on dry roads and from 0.25g to 0.5g on wet roads (Henderson, 1987). In the model, emergency deceleration of the following vehicle was treated as a random number having a normal distribution with a mean of 0.6g and a standard deviation of 0.1g. This distribution was bounded by a minimum value of 0.3 g and a maximum value of 0.8 g. Finally, a constant time delay of 0.15 second was added to driver braking response time to account for vehicle time delay needed to reach a maximum deceleration.

3.11.4 Monte Carlo Simulation Results

Computer simulations were executed to estimate the probabilities of a crash in two pre-crash scenarios for manual driving, CCC, and ICC. The scenarios were distinguished by whether the lead vehicle suddenly decelerated, or the lead vehicle was traveling at a lower speed when encountered by the following vehicle. In the former scenario, sudden lead vehicle deceleration was induced in each simulation run by using a random number from the "lead vehicle deceleration" variable in conjunction with a data triad of vehicle velocity, range, and range-rate as initial conditions. In the latter scenario, only data triads with negative range-rate values were used (following vehicle velocity > lead vehicle velocity).

3.11.4.1 Results of Lead Vehicle Deceleration Scenario. Table 3-62 shows a comparison of estimated probabilities of a crash in pre-crash scenario 1 between ICC and manual modes. In addition, the resulting absolute effectiveness (E) values, $1 - [p_{ICC}(bin_j)/p_{manual}(bin_j)]$, and the actual effectiveness values, $E_a(1,j) = E(1,j) \times P(1,j) \times u_{ICC}(j)$, are shown. The results for CCC are shown in Table 3-63. Recall that absolute effectiveness values consider the triad data for the appropriate velocity bin, but do not take into account the rear-end pre-crash scenario relative frequency and the actual time spent within a bin. The actual effectiveness takes into account rear-end pre-crash scenario relative frequencies and proportions of time ICC and CCC systems were used in a particular velocity bin. Usage rates of ICC and CCC observed in the FOT are utilized in these tables. For the pre-crash scenario where the lead vehicle suddenly decelerates, when the ICC system and the CCC system were assumed to be on when the scenario began, rear-end collisions on freeways would have been reduced 11.8 percent and 4.1 percent respectively. The projected benefits assume that all vehicles are equipped with the given system, and that the system is used on freeways the same percentage of the time that the system was used by participants in the FOT. Finally, the simulations of rear-end pre-crash scenario 1 suggest that the ICC system would be more effective than the CCC system at all travel velocities on freeways.

Table 3-62 ICC Rear-End Pre-crash Scenario 1 Simulation Results

	40 – 56	*56 - 73*	*73 - 89*	*89 - 97*	*97 - 105*	*105 - 113*	*113 - 121*	*≥121*
Manual (p_{wo})	0.03631	0.02187	0.01711	0.01668	0.01285	0.01319	0.01255	0.01290
ICC (p_w)	0.01995	0.01212	0.00935	0.00646	0.00560	0.0044	0.00489	0.00601
Absolute Effectiveness	0.4506	0.4458	0.4535	0.6127	0.5642	0.6664	0.6104	0.5341
Actual Effectiveness	0.0014	0.0068	0.0307	0.0234	0.0229	0.0213	0.0096	0.0020

Table 3-63 CCC Rear-End Pre-crash Scenario 1 Simulation Results

	40 - 56	*56 - 73*	*73 - 89*	*89 - 97*	*97 - 105*	*105 - 113*	*113 - 121*	*³121*
Manual (p_{wo})	0.03631	0.02187	0.01711	0.01668	0.01285	0.01319	0.01255	0.01290
CCC (p_w)	0.00042	0.00284	0.00771	0.00706	0.00572	0.00636	0.00914	0.01232
Absolute Effectiveness	0.9884	0.8701	0.5494	0.5767	0.5549	0.5178	0.2717	0.0450
Actual Effectiveness	0.0001	0.0024	0.0078	0.0066	0.0113	0.0104	0.0026	0.0001

3.11.4.2 Results of Lead Vehicle at Lower Velocity Scenario. Tables 3-64 and 3-65 list values of the estimated actual effectiveness of the ICC and CCC systems in preventing rear-end collisions on freeways in each of the eight travel velocity bins, where the lead vehicle is traveling at a lower velocity than the following vehicle. Assuming usage rates observed in the FOT, the ICC system effectiveness in this scenario was estimated at about 26.6 percent yielding a substantial reduction in rear-end collisions that are preceded by this pre-crash scenario on freeways. Conversely, the CCC system was estimated to contribute to an increase of about 1.6 percent in rear-end collisions on freeways which are preceded by this pre-crash scenario. The negative value of CCC system effectiveness resulted from closing velocities in the CCC mode, which were higher than those in the manual control mode.

Table 3-64 ICC Rear-End Pre-crash Scenario 2 Simulation Results

	40 - 56	*56 - 73*	*73 - 89*	*89 - 97*	*97 – 105*	*105 - 113*	*113 - 121*	*³121*
Manual (p_{wo})	0.00532	0.00398	0.00330	0.00316	0.00129	0.00075	0.00049	0.00108
ICC (p_w)	0.00037	0.00051	0.00128	0.00103	0.00040	0.00035	0.00024	0.00015
Absolute Effectiveness	0.9301	0.8731	0.6123	0.6726	0.6884	0.5411	0.5184	0.8609
Actual Effectiveness	0.0013	0.0075	0.0222	0.0461	0.0435	0.0635	0.0305	0.0513

Table 3-65 CCC Rear-End Pre-crash Scenario 2 Simulation Results

	40 - 56	*56 - 73*	*73 - 89*	*89 - 97*	*97 - 105*	*105 - 113*	*113 - 121*	*³121*
Manual (p_{wo})	0.00532	0.00398	0.00330	0.00316	0.00129	0.00075	0.00049	0.00108
CCC (p_w)	0	0	0.00099	0.00343	0.00088	0.00079	0.00097	0.00183
Absolute Effectiveness	1.0000	1.0000	0.7012	-0.0861	0.3209	-0.0419	-0.4959	-0.4113
Actual Effectiveness	0.0000	0.0015	0.0053	-0.0018	0.0102	-0.0031	-0.0177	-0.0110

3.11.5 Summary of Widespread Safety Effects Findings

Approximately one hundred thousand Monte Carlo computer simulations were run for each of the two rear-end pre-crash scenarios in each of the eight velocity bins, and for each cruise mode, for a total of about 4,800,000 runs. Taking the two scenarios together, the ICC system effectiveness was estimated at approximately 17 percent for rear-end collisions on freeways at travel velocities above 40 km/h, assuming (a) all vehicles were equipped with the system, and (b) the system was used with the same frequency as was observed in the field operational test. However, the simulations only considered lead and following vehicle behavior, not the effects of the system on traffic flow, or the appropriateness of using the ICC system under various traffic conditions. The analysis did not consider, for instance, the effects of ICC on the stability of strings of equipped vehicles, as has been discussed by Bogard et al. (1998) and Swaroop (1997). Thus, the results reported here are limited to crash risk between a lead and following vehicle, when range, range-rate, and velocity are considered. Nevertheless, the results indicate a fairly strong benefit for ICC compared to manual driving.

Assuming the results reported here generalize to the case of full system deployment, the ICC system could have reduced the number of police-reported rear-end collisions on freeways by about 13 thousand in 1996. This estimate is based on 1996 GES statistics, and assumes the ICC system usage would be the same as that observed in the ICC FOT. The analysis further showed that the time-headway maintenance feature of the ICC system was responsible for the projected benefit, as benefits with the CCC system were almost negligible. The overall total system effectiveness of CCC taking the two scenarios together was estimated at about 2 percent for rear-end collisions on freeways at travel velocities above 40 km/h.

It should be noted that the ICC system has the potential to reduce more rear-end collisions if road classes other than freeways were considered in this analysis. As Figure 3-9 indicates, test drivers did engage the ICC system in the FOT for small proportions of time on arterials (6 percent) and state highways (11 percent). Finally, additional safety benefits could be accrued through the use of ICC systems if such systems detected and responded to stationary objects in the forward path of the equipped vehicle.

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4. User Acceptance of the ICC System

This chapter presents questionnaire and focus group findings that are related to user acceptance of the ICC system, but not directly related to user perceptions of safety benefits. User perceptions related to safety are covered in Chapter 3.

4.1 Objectives

The purpose of the user acceptance analysis was to address the following key questions:

1. ***Do drivers like the ICC system?***
   - Do drivers prefer ICC to manual headway control and CCC?
   - Do drivers consider driving with the ICC system more convenient, comfortable, and enjoyable than manual driving or CCC?
   - Did drivers become comfortable with the ICC system during the time they had to experience it?
   - On what types of roadway would drivers most likely use ICC?
   - Do drivers feel comfortable using the ICC system on hilly and winding roads?
   - Do drivers feel comfortable using the ICC system in rain and snow?
   - Do drivers feel comfortable if ICC systems replaced CCC systems?
2. ***Are ICC drivers willing to pay for an ICC-like system?***
   - How much would drivers be willing to pay for an ICC-like system?
   - What is the likelihood that drivers would purchase an ICC-like system?

The following sections report on the findings with respect to the above questions.

4.2 Results

4.2.1 Do Drivers Like the ICC System?

Several questionnaire items were analyzed to determine whether users perceived the ICC system to be desirable. It was assumed that drivers would desire to own and use the ICC system if they reported that they were comfortable using it, enjoyed using it, found it convenient to use, and, especially, preferred driving with it to driving without it. These issues are examined below.

Do drivers prefer ICC to manual headway control and CCC? Users were asked to rank the preference “for personal use” of ICC, CCC and manual “modes of operation”, where 1 represented most preferred and 3 represented least preferred. The mean ranks from responses to this question are represented in Figure 4-1. Preferences were dependent on previous experience with cruise control. Participants who said they had been cruise control users before participating in the FOT ranked ICC as their most preferred mode, followed by manual and CCC. The rankings were significantly different from equal probability, C^2 (2) = 31.7, $p < 0.001$.[1] As can be clearly seen from Figure 4-1, the preference of prior users for ICC over manual and CCC is significant. The preferences for manual and CCC are significantly less than ICC and are essentially equal. Those who did not claim to be prior users of cruise control on average ranked manual as most preferred, followed by ICC, and then CCC, C^2 (2) = 92.7, $p < 0.001$. Unlike users, there was considerable variation in their responses, indicating substantial disagreement among nonusers on which mode they preferred.

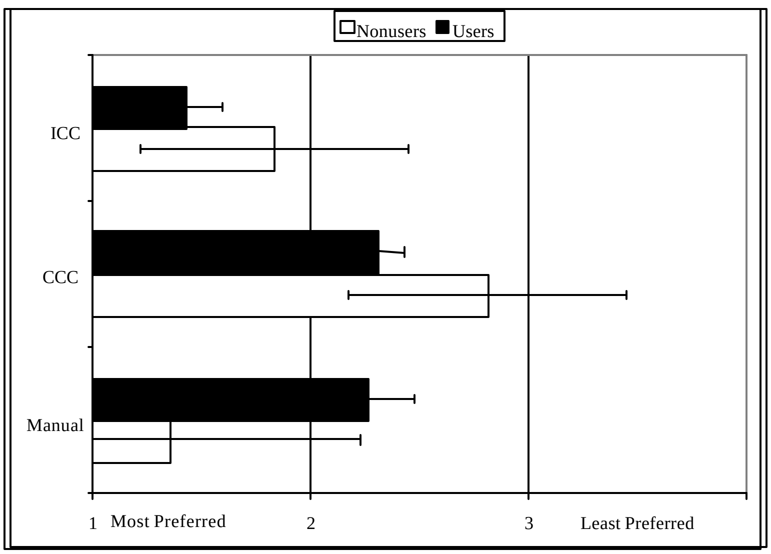

Figure 4-1 Rankings Based on Responses to the Request to “Rank, in Order of Preference, the Following Modes of Operation for Personal Use”

Overall, drivers clearly preferred ICC over CCC, but the preference of ICC over manual was equivocal. Participants who said they were already cruise control users ranked ICC as their most preferred mode. Those who said they didn’t use cruise control ranked manual control as slightly (not reliably) preferable to ICC. The non-users on average, however, preferred ICC (and manual) over CCC. As we saw in Chapter 3, cruise control users used ICC more than nonusers, so that in this instance the stated preferences are consistent with actual usage. The

[1] Significance tests using the Chi-square statistic tested the hypothesis that the mean rankings were equal, e.g., for this test that the mean rank of all three items was 2. The finding that the ranks were not equal implies that at least one of the items was ranked significantly higher, or lower, than 2.

overall preference of ICC over CCC by both users and nonusers is also consistent with actual usage results presented in Chapter 3.

Do drivers consider driving with the ICC system more convenient, comfortable, and enjoyable than manual driving or CCC? In addition to the question about which cruise modes participants preferred to use, the questionnaire asked the respondents to rank the three modes with respect to driving comfort, convenience, and enjoyment. The mean preference rankings for comfort, convenience, and driving enjoyment are shown, in Figure 4-2. For all three of these attributes, as can be seen from the figure, users overwhelmingly chose ICC. There were no differences in rankings as a function of age group, previous cruise control use, gender, or duration of the ICC experience (one week or four weeks). It is interesting to note that the cruise control nonusers shown in Figure 4-1 tended to prefer manual mode for "personal use" but clearly preferred ICC for "comfort", "convenience", and "driving enjoyment". This may be an indication that nonusers generally do not like to use cruise control of any kind for reasons other than comfort, convenience, and enjoyment, such as a desire to be more actively in control of the vehicle. For all attributes, the mean ranks of the cruise modes were significantly different from equality, $p < 0.001$ by Friedman's C^2.

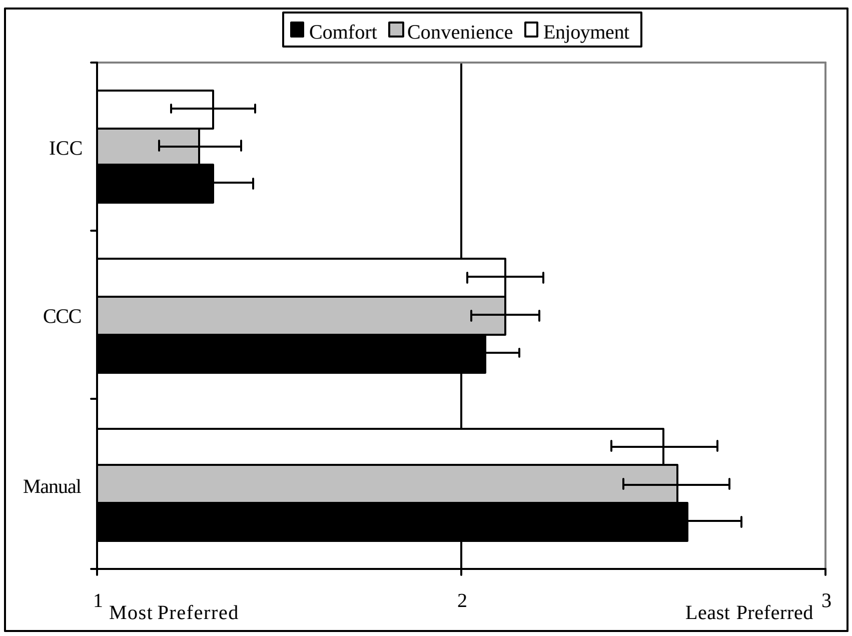

Figure 4-2 Rankings in Response to Request to Rank the Three Modes of Operation with Respect to Comfort, Convenience, and Driving Enjoyment

Did drivers become comfortable with the ICC system during the time they had to experience it? As shown in Figure 4-3, participants who had the ICC vehicle for two weeks (and use of ICC for one week) indicated that they thought it was likely that, with experience, they would have become more comfortable with the ICC system. Participants who had four weeks of exposure to the ICC system were less likely to indicate that they would have become more comfortable with the system, given additional exposure. The difference in rating between two- and five-week participants was reliable, $F(1, 106) = 49.0$, $p < 0.01$. This finding is, perhaps, not surprising, but it does contrast with the lack of a reliable difference between these groups in the high comfort ratings. This finding also seems to suggest that the ICC system introduces a new dimension to driving that may require a learning process of more than a week before drivers feel fully comfortable with it. To the extent that there is a learning process, consideration of orientation and training of new users may be appropriate.

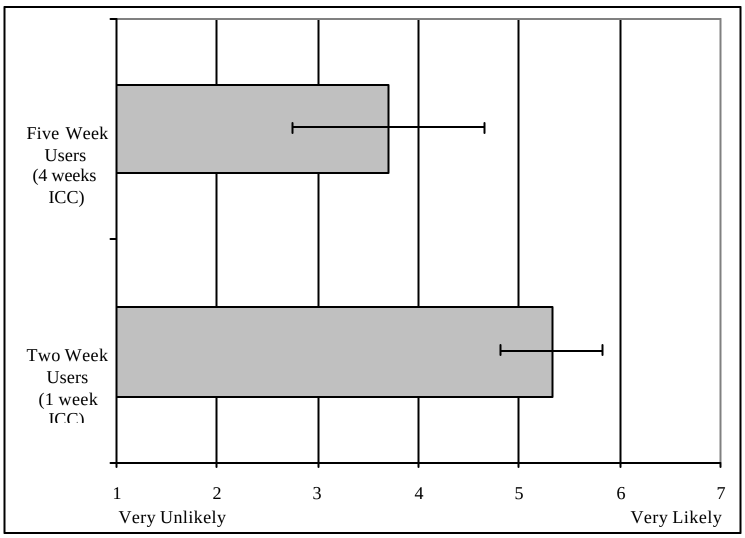

Figure 4-3 Participants' Ratings of the Likelihood that, Given More Time, They Would Have Become More Comfortable with the ICC System

On what types of roadway would drivers most likely use ICC? Ratings of likelihood to use each cruise mode as a function of road type are shown in Figure 4-4. Consistent with actual usage, the participants indicated that they were most likely to use ICC on freeways, and most likely to drive manually on arterials. The participants also indicated that they were approximately equally likely to use ICC or manual on 2-lane and rural roads, but unlikely to use CCC on those roads (the rankings for ICC and manual were not significantly different on these roads, $p > 0.50$). Actual usage on 2-lane and rural roads could not be compared with the stated preference, because the GPS road classification information did not distinguish 2-lane and rural roads from state highways.

The developers of the ICC system that was tested viewed the ICC system as primarily useful on freeways (Fancher, et al, 1998)[2] and designed the system accordingly. The questionnaire data suggest that participants also viewed use of ICC on 2-lane and rural roads as appropriate, and some viewed use on arterials as appropriate. This suggests that developers of ICC-like systems need to address system performance on 2-lane and rural roads, as well as to performance on freeways. For example, developers may need to consider ICC performance on hills and curves that are more severe than found on freeways and also to false targets that are more likely to be generated by roadside objects and opposite lane traffic than on freeways.

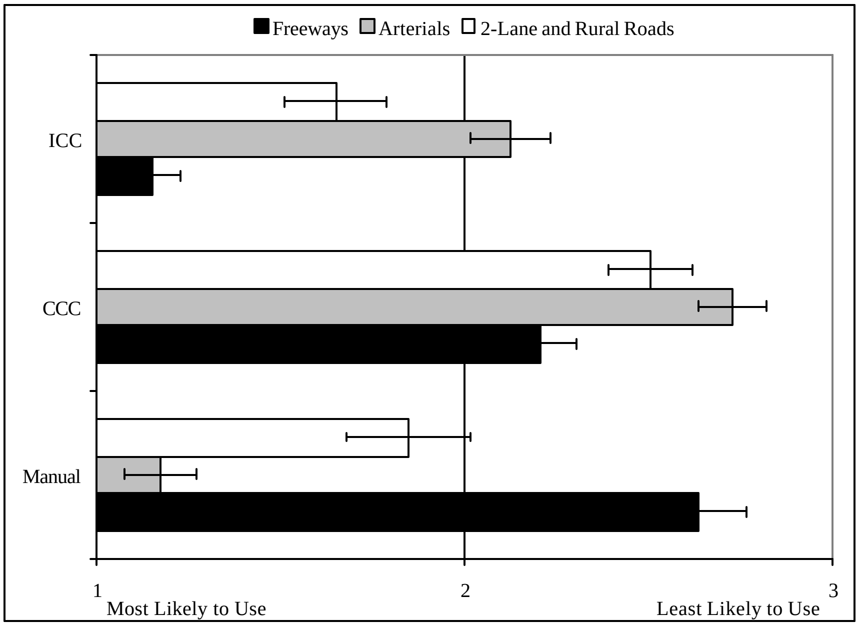

Figure 4-4 Participants' Rankings of Cruise Modes with Respect to "Which Mode of Operation Were You Most Likely to Drive…" on Three Road Types

Do drivers feel comfortable using the ICC system on hilly and winding roads?
Figure 4-5 shows participants' ratings of "how comfortable" they were using the ICC system on winding roads and hilly roads. On average, those participants who indicated that they had driven in those conditions rated the experience as comfortable. These ratings did not vary with age group, previous cruise control use, or gender. In spite of the concern expressed above regarding performance of future ICC-like systems on 2-lane and rural roads, these results suggest that the ICC system, as tested, performed to a reasonable level of user comfort under these difficult conditions.

The ICC system used in the FOT was not fully capable of tracking preceding vehicles on more severe hills and curves. However, participants indicated that they felt a fair degree of comfort in

[2] For example, on page one of FOT final report the authors stated that the ICC system enabled drivers to "…proceed through moderate freeway traffic without adjusting cruise buttons or touching the throttle or brake".

using the system on hilly and winding roads. As indicated above, system designers should consider the likelihood that ICC systems will be used in these environments

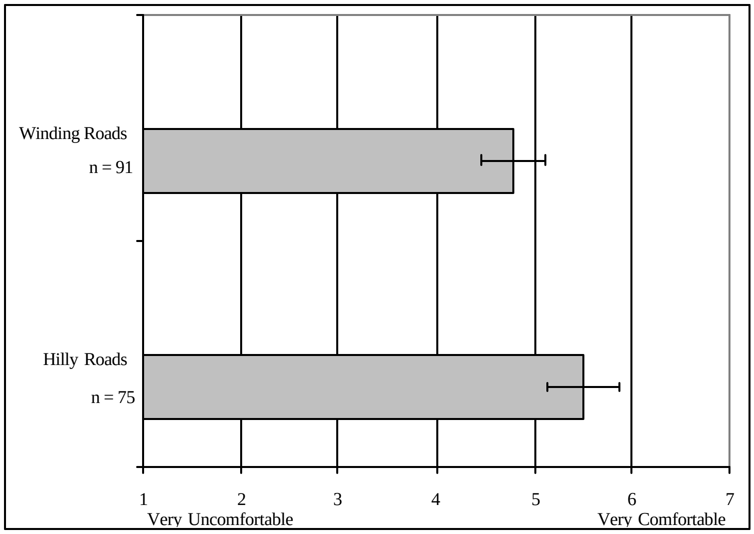

Figure 4-5 Participants' Ratings of Comfort with ICC System on Hilly and Winding Roads

Do drivers feel comfortable using the ICC system in rain and snow? Participants were asked to rate how comfortable they were using ICC and CCC in rain and snow. Only a few participants had the opportunity to use the system in snow. Therefore we assume that the responses refer primarily to rain. Responses, shown in Figure 4-6, varied depending on whether or not the participants were previous cruise control users.

Members of both prior cruise control user and nonuser groups failed to show consensus as to whether ICC or CCC use was comfortable in rain or snow. The mean comfort ratings for ICC were slightly favorable. The mean CCC comfort rating from nonusers of cruise control was slightly negative, which indicated that, on average, non-cruise control users are somewhat uncomfortable with CCC use in rain or snow – not a surprising finding given that they don't use CCC in fair weather either. Interestingly, prior users of cruise control expressed greater comfort with the CCC in rain and snow than they did for ICC. The less than overwhelming expressions of comfort with ICC use in rain and snow, which contrasts sharply with overall comfort ratings shown in Figure 4-2, may be associated with sensor problems than were documented during the FOT. In particular, snow could blind the sensor in such a way that it failed to detect preceding vehicles and failed to detect any limitation of its capability to detect vehicles. Road spray could cause similar problems, and could also cause false targets to be identified. Designers of future ICC-like systems will need to address these issues.

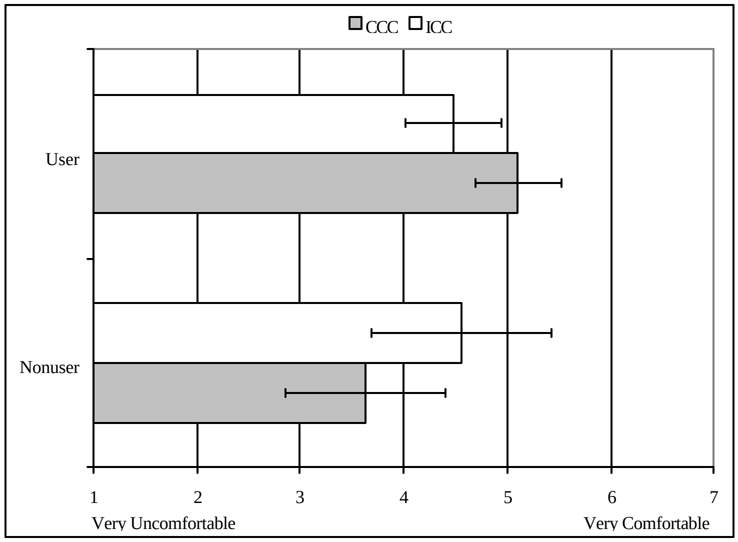

Figure 4-6 Comfort Ratings for Use of ICC and CCC in Rain and Snow

Do drivers feel comfortable if ICC systems replaced CCC systems? As shown in Figure 4-7, participants indicated that they would be quite comfortable if ICC systems were to replace CCC systems. Though all age groups indicated they would be comfortable with this eventuality, there was a significant difference among the age groups, $F\ (2, 101) = 3.1$, $p < 0.05$. The middle-age group indicated significantly greater comfort with ICC replacing CCC than did the older and younger groups. This result suggests wide marketplace acceptance of ICC-like systems.

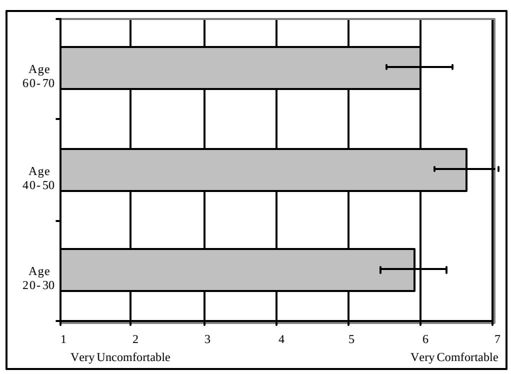

Figure 4-7 Participant Comfort with Possibility that ICC Systems Would Replace CCC Systems

Summary of Preference Questionnaire Results: Based on the above findings, it is reasonable to conclude that participants liked the ICC system, and found it preferable to conventional cruise control. Both prior users of CCC and nonusers of CCC preferred the ICC to CCC, although nonusers still preferred manual to either cruise control mode. Participants overwhelmingly ranked ICC over CCC and manual for convenience, comfort, and enjoyment.

Participants, particularly those who had the ICC system for only one week, indicated that they would be more comfortable with the system given more time. This indicated that ICC driving may be sufficiently complex as to require more than a week of experience to be fully comfortable with the system. This suggests that special orientation and training of future ICC users may be appropriate.

Participants would most likely use ICC on freeways; however, a significant number were comfortable using it on 2-lane rural roads. This suggests that future ICC systems should be designed with their use on secondary roads in mind (for example by accommodating narrow lanes, sharp curves, and more rolling hills).

Both users and nonusers of cruise control were comfortable with the ICC in rain and snow, but users were less comfortable with ICC than CCC. This suggests that future ICC-like systems will need to resolve the rain and snow related sensor problems that were documented during the FOT.

Overall there was a high level of comfort in seeing ICC replace CCC in future vehicles, particularly amongst the 40-50 year-old participants.

4.2.2 Are Drivers Willing to Pay for an ICC-like System?

The second part of the questionnaire was aimed at determining measures of consumer interest for ICC based on the participants' FOT experience. The issues of price and likelihood of purchase are discussed below.

How much would drivers be willing to pay for an ICC-like system? In the questionnaire, respondents were asked to state how much they would be willing to pay for an ICC-like system in a new vehicle. Most provided a dollar value. A few stated that they would pay the same amount as for a conventional cruise control system, or provided a dollar amount that they would be willing to pay above the amount that a CCC system would cost. For those respondents who provided amounts relative to the cost of CCC, the value of $200 was assumed for CCC. Ninety-one respondents provided either a dollar amount, or an amount relative to CCC. Prior users of cruise control were willing to pay more for an ICC system than were prior nonusers, F (1, 96) = 4.5, $p < 0.05$.

Figure 4-8 shows the distribution of willingness to pay estimates, where 100 percent of users are shown to be willing to pay $0 and the medians were approximately $275 and $475 for nonusers and users, respectively. The overall median for all 91 respondents was $300. As will be seen in Chapter 5, the median willingness to pay estimates are somewhat less than projections for the market cost of ICC systems.

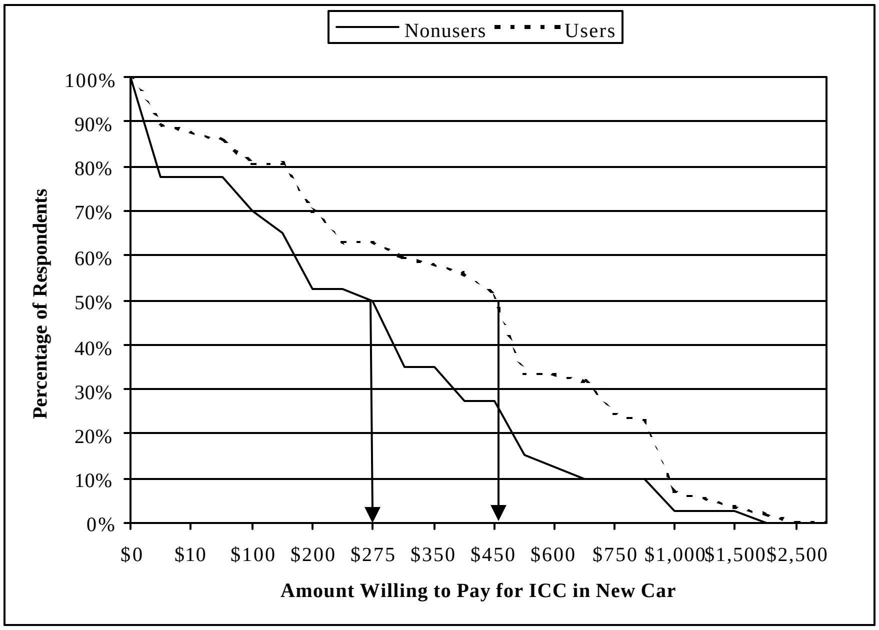

Figure 4-8 Cumulative Distribution of Willingness to Pay Estimates of Prior Users and Nonusers of Conventional Cruise Control

What is the likelihood that drivers would purchase an ICC-like system? Participants were also asked how willing they would be to purchase an ICC system with a new car. The willingness to purchase ratings are shown in Figure 4-9. Overall, the participants were very willing to purchase the systems. Nonusers were slightly less strong in their rating of willingness to purchase, $F(1, 106) = 6.2$, $p < 0.05$. Middle-aged participants were most enthusiastic in their willingness to purchase estimates, which was reflected in a significant age effect, $F(2, 106) = 4.8$, $p < 0.05$. This is consistent with the previous finding that middle-aged drivers were most comfortable with ICC systems replacing CCC systems (see Figure 4-7). Older nonusers were significantly less willing than older users to purchase an ICC system, but a similarly significant difference between users and nonusers did not appear in the other age groups.

The data suggest that many participants liked ICC well enough to be willing to pay around $300 for it, with a high likelihood that they would purchase the system at that price. Furthermore, most respondents indicated that they would be “very willing” to rent a vehicle equipped with an ICC system.

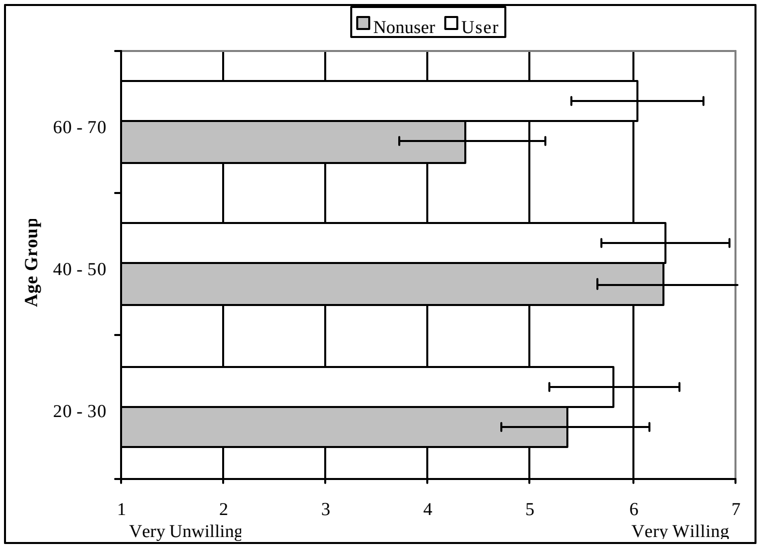

Figure 4-9 Willingness to Purchase ICC with a New Car Ratings

Summary of Willingness-to-Pay Questionnaire Results: On the whole, drivers were comfortable with paying about $300 for an ICC system when buying a new car, or paying an equivalent rental supplement. Prior cruise control users reportedly would pay more than $450, and non-users $275. Drivers of each age group expressed more than neutral willingness to pay for ICC, with users significantly more willing. The difference in likelihood of purchase between users and non-users, however, was not so apparent in the middle 40-50 year age group. Middle-aged users express uniformly high willingness-to-purchase, consistent with their prior indications of ICC comfort and acceptance.

5. Deployment Issues

The ICC FOT provided an excellent opportunity to observe how individual users would use ICC. However, it did not provide an opportunity to observe what might occur on the roadway system if all or most vehicles were equipped with, and using, ICC. One objective of this section was to extrapolate from the empirical FOT data to obtain insight into what the impacts of full scale ICC system deployment might be. To achieve this goal, we first examine what the impacts of ICC deployment might be on traffic flow in Section 5.1.

Following examination of potential traffic flow impacts, Section 5.2 estimates the impacts of the ICC system deployed in the FOT on fuel consumption and emissions.

For ICC system deployment to affect future safety, traffic flow, fuel consumption, or emissions, the system must achieve some level of market penetration. In Section 5.3 an analysis is presented on the future costs of ICC systems to the consumer. This analysis presents data from a recently deployed technology, i.e., anti-lock braking systems, as well as early estimates of ICC system costs, and comparisons of projected ICC costs with willingness to pay projections from Chapter 4.

The final section in this chapter discusses institutional impediments to deployment of ICC-like systems.

5.1 Traffic Flow

Before examining the potential impacts of full deployment of ICC-like systems on traffic flow, some fundamentals of roadway performance measurement are explored.

5.1.1 Measuring Traffic Flow Performance

Conceptual understanding of traffic flow performance has been expanding to deal with the phenomena of roadway congestion. Traditionally, roadway *carrying capacity* was a key element in describing traffic flow performance. Traffic engineers used a demand-to-supply measure such as the *volume-to-capacity ratio*. Roadway carrying capacity was defined as the maximum number of vehicles that could pass a point along a roadway in a given period of time. Traffic congestion was narrowly defined as a situation that occurred when traffic demand exceeded the capacity of a roadway at one or more points. This suggests that traffic congestion can only be caused by excess vehicle demand. However, the understanding of the traffic flow performance has expanded away from demand-supply measures to congestion and mobility measures.

Congestion is measured in terms of *traffic density*. For example, the *Highway Capacity Manual* (1997) relates the quality of traffic flow on freeways to traffic density in units of passenger cars per mile per lane. This measure suggests that congestion is not merely a situation where volume exceeds capacity, but one in which there are “too many cars on the road” or the roadway is “too crowded”. Both of these concepts are directly related to traffic density. Density also provides a basis for quantifying the severity of congestion, whereas capacity only provides a boundary defining where it begins.

Mobility is measured in terms of *throughput*. Throughput is the product of the speed of traffic and the volume of traffic being carried. The volume being carried is referred to as the *flow rate*. Maximum throughput occurs when the product of speed and flow is the highest. The throughput concept recognizes the role that speed plays on mobility and congestion. Adding lanes can increase capacity to handle more cars, but increasing speed can reduce the amount of time necessary to complete a trip, and thereby can reduce the time that vehicles occupy space on the roads. Both adding capacity and increasing speed can help reduce density, and thereby congestion.

Throughput is a measure of how effectively a roadway segment serves demand. The units of throughput come from volume (vehicles per hour) and speed (kilometers per hour) that combine to produce a unit of vehicle kilometers per hour per hour.

5.1.2 Measures of Vehicle Separation

ICC is controlled by two user-defined operating parameters: a *set speed* which defines the desired speed of travel, and a vehicle spacing measure called the *time-headway* setting. CCC only uses the set speed parameter. Because the ICC definition of time-headway is not consistent with the traffic engineering definition of time-headway, the following discussion is presented to clarify measures of vehicle separation in space and time.

Figure 5-1 illustrates the relationship between various measures of vehicle spacing used in traffic flow theory, and their relation to measured ICC variables. Working definitions of vehicle spacing measures are:

- **Space headway –** the distance between the front bumper of a vehicle and the front bumper of the vehicle it is following (meters per vehicle).
- **Gap –** the distance between the front bumper of a vehicle and the back bumper of the vehicle it is following (meters). Gap is analogous to the ICC *range* variable.
- **Vehicle Length –** the length of the vehicle from the front to the back bumper (meters). The difference between the space headway and the gap is also equal to the vehicle length.

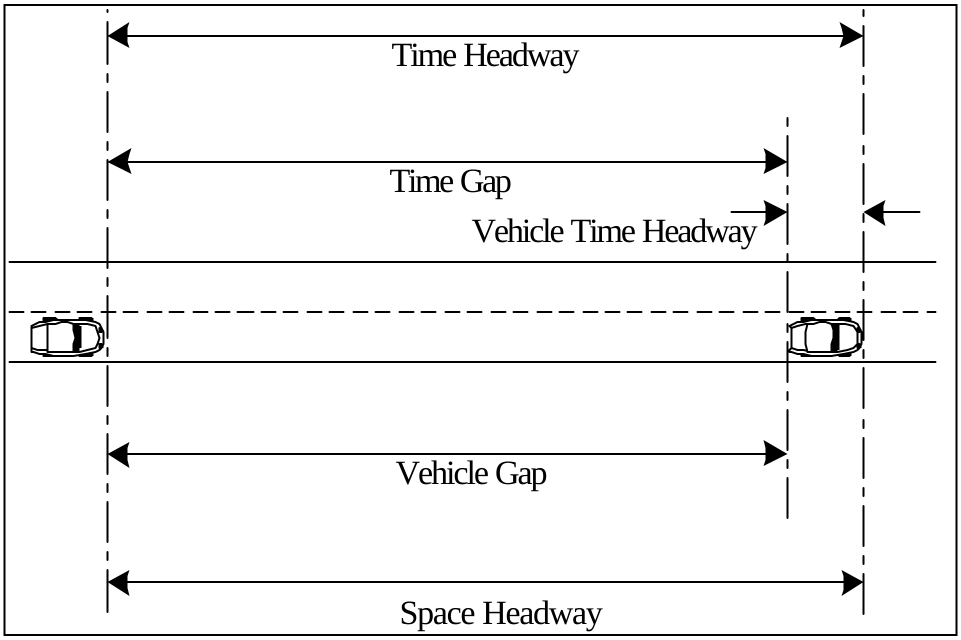

Figure 5-1 Measures of Vehicle Spacing

The spacing of vehicles in time is broken into the same conceptual components as distance measures:

- **Time-headway** – the time between the passage across a given stationary point of the front bumper of a vehicle and the front bumper of the following vehicle (seconds per vehicle).
- **Time gap** – the time between the passage across a given stationary point of the back bumper of a vehicle and the front bumper of the following vehicle. Time gap is analogous to the “time-headway” measure in Chapter 3.0.
- **Vehicle time-headway** (or passage time) – the time between the passage across a given stationary point of the front bumper of a vehicle and its back bumper. Vehicle time-headway is the difference between the time-headway and the time gap. Vehicle time-headway is inversely proportional to speed, and is calculated by dividing the length of a vehicle by the speed in which it is traveling.

What is referred to in most of this report, and in other ICC FOT documents as “time-headway” has traditionally been referred to as “time gap” (May, 1990). Though this distinction has less relevance in other ICC FOT documents, it is important to distinguish the difference when describing the implications of ICC on throughput. Time gap is the time between the passage of the rear bumper of one vehicle and the front bumper of the following vehicle. Traditional time-headway is measured between the front bumper of each vehicle. Therefore, in order to compute *traditional time-headway*, *vehicle time-headway* must be added to the ICC *time gap*. ICC time gaps could be set to 1.0, 1.4 or 2.0 seconds. The vehicle time-headway is computed by dividing the length of the vehicle by the speed at which it is traveling. Therefore, vehicle time-headway is not a constant. As a result, the time gap settings used by ICC translate to variable time-headways that are an inverse function of speed. Note that space headways increase with speed if time-headways are held constant.

5.1.3 Relationship between Speed, Time-headway and Capacity

The capacity of a roadway is the maximum rate of traffic flow that can be reasonably sustained over a period of time – usually one hour. For roadways designed for continuous traffic flow (i.e., no traffic signals), roadway capacity is computed using the minimum average (traditional) time-headway of vehicles traveling in a lane. The lane capacity of a roadway, in vehicles per hour, is computed by taking 3,600 seconds per hour and dividing by the minimum average (traditional) time-headway in seconds per vehicle.

Recent freeway operations research performed for the *Highway Capacity Manual* (1997) in NCHRP 3-45 has shown that higher traffic flow rates (capacity) can be achieved if vehicles are able to travel at higher speeds. For example, according to the *Highway Capacity Manual* chapter on *Basic Freeway Sections,* freeway lane capacities increase from 2250 to 2400 passenger cars per hour per lane when speeds at-capacity increase from 49 to 55 miles per hour. On many freeways, flow rates as high as 2,800 passenger cars per hour per lane are experienced regularly in the left-most, or "high speed" lane, where trucks are restricted, and speed at-capacity exceeds 72 miles per hour.

Speed-flow relationships developed in NCHRP 3-45 suggest that at freeway speeds, and flows near capacity, space headway increases by only small amounts as speed increases through the normal range of freeway operating speed. If space headway remains fairly constant while speed increases, then time-headway decreases, and capacity is increased. Higher capacities can also be achieved by reducing the time-headway between vehicles traveling at any given constant speed. There are, of course, practical limitations to maximum speed and minimum headway. Roadway design elements and speed limits constrain maximum speed. Minimum headway reflects driver comfort thresholds. These thresholds are related to drivers' perceptions of their ability to detect and respond to hazards. Limits for minimum headway are dependent on a number of factors that include driver reaction time, driver confidence in the vehicle's braking or maneuvering performance, and weather conditions.

Based on the results of studies performed for the *Highway Capacity Manual*, the rate of flow at-capacity is related to speed by the equation:

$$S = 0.004708\, F_c + 0.0000075868\, F_c^2$$

where:

S represents speed of traffic when flows are at capacity (miles per hour)

F_c represents flow at-capacity (vehicles per hour per lane).

This relationship was developed using empirical data from freeway facilities. If the relationship is applied in a parametric analysis using flow levels from zero to 3,000 vehicles per hour per lane, traffic densities at each speed can be calculated as flow divided by speed. Space headway can be calculated at 5,280 feet per vehicle divided by the density. Time-headway can be calculated as 3,600 seconds per hour divided by the flow rate. Table 5-1 shows computed values for these traffic parameters at various flow levels. Note that time-headway declines quickly at first, but begins to level off when it falls below two seconds per vehicle at flows over 1,800 vehicles per hour per lane. Time-headway reaches 1.2 seconds per vehicle at a flow of 3,000 vehicles-per hour-per-lane.

Table 5-1 Freeway Traffic Characteristics with Flow Rates at Capacity

Flow Rate (vphpl)	*Speed (mph)*	*Density (vpmpl)*	*(Traditional) Time-Headway (sec/veh)*	*Vehicle Time- * Headway (sec/veh)*	*Space Headway (ft/veh)*
0	—	211.2	—	—	25.0
200	1.2	160.6	18.0	9.31	32.9
400	3.1	129.2	9.0	3.74	40.9
600	5.6	108.0	6.0	2.09	48.9
800	8.6	92.8	4.5	1.34	56.9
1000	12.3	81.3	3.6	0.94	64.9
1200	16.6	72.4	3.0	0.70	72.9
1400	21.5	65.2	2.6	0.54	80.9
1600	27.0	59.4	2.3	0.43	89.0
1700	29.9	56.8	2.1	0.39	93.0
1800	33.1	54.5	2.0	0.35	97.0
1900	36.3	52.3	1.9	0.32	101.0
2000	39.8	50.3	1.8	0.29	105.0
2100	43.3	48.4	1.7	0.27	109.0
2200	47.1	46.7	1.6	0.25	113.0
2250	49.0	45.9	1.6	0.24	115.0
2300	51.0	45.1	1.6	0.23	117.0
2350	53.0	44.4	1.5	0.22	119.0
2400	55.0	43.6	1.5	0.21	121.0
2450	57.1	42.9	1.5	0.20	123.0
2500	59.2	42.2	1.4	0.20	125.0
2550	61.3	41.6	1.4	0.19	127.0
2600	63.5	40.9	1.4	0.18	129.0
2650	65.8	40.3	1.4	0.18	131.0
2700	68.0	39.7	1.3	0.17	133.0
2750	70.3	39.1	1.3	0.16	135.0
2800	72.7	38.5	1.3	0.16	137.0
2850	75.0	38.0	1.3	0.15	139.0
2900	77.5	37.4	1.2	0.15	141.0
2950	79.9	36.9	1.2	0.15	143.0
3000	82.4	36.4	1.2	0.14	145.0

Vphpl vehicles per hour per lane
mph miles per hour
vpmpl vehicles per mile per lane

* Vehicle time headway computed based on a 17-foot average vehicle length.

Lane changing is another factor that affects both speed and capacity. When a vehicle changes lanes on a roadway operating at high flows, a small shock wave emanates upstream from the point at which that vehicle intrudes on the gap in front of another vehicle. Beginning with the latter vehicle, all vehicles upstream must slow until normal time-headway is restored. This is the primary reason why the speed of freeway traffic at high flows (above 60 to 75 percent of capacity) begins to decline as flow rates approach capacity. On basic freeway sections (with no ramps and weaving sections), this speed drop is about 20 percent below the free flow speed (free flow speed is the prevailing speed of traffic at low flows). On freeway sections with ramps and weaving sections, larger speed drops occur, sometimes in excess of 50 percent. When these speed drops occur, the flow of traffic will break down at a lower flow rate than it would at a higher speed. In other words, capacity will decrease. Figure 5-2 shows typical speed-flow curves for various freeway situations, as well the curve from the speed-capacity equation given above.

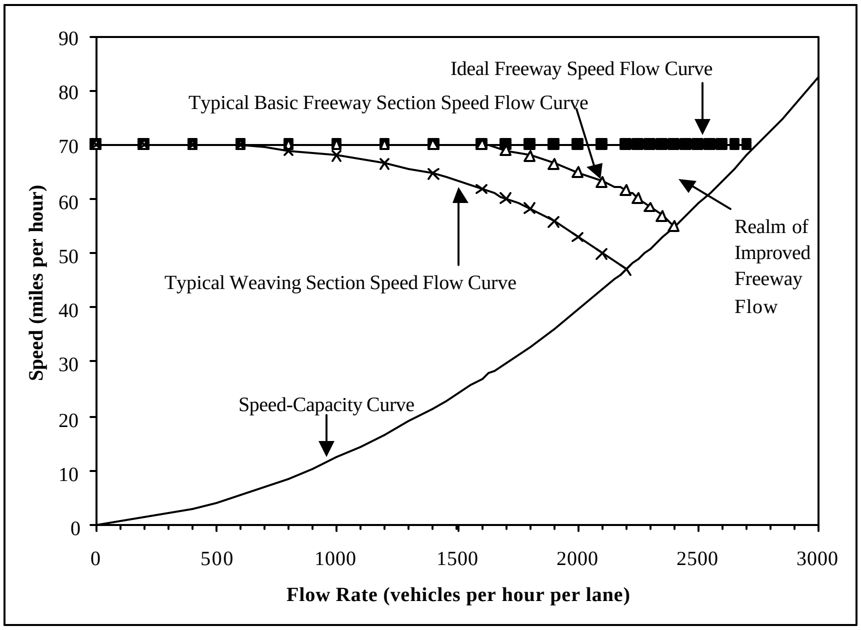

Figure 5-2 Freeway Speed-Flow Relationships.

Theoretically, on freeways with no lane-changing turbulence and no drivers traveling dramatically slower that the free flow speed, there would be no loss of speed as flow approaches capacity. This theoretical relationship can sometimes be observed in the left-most through lane on freeways, where vehicles travel at high speeds with little or no interference from merging, diverging, weaving, or other lane changing maneuvers and achieve very high flows. Under these undisturbed conditions, high lane capacities are realized. The undisturbed free flow state is illustrated in Figure 5-2 as the area labeled “Realm of Improved Freeway Flow”.

5.1.4 Impact of User-defined Headways on Capacity

Assuming full market penetration of ICC and full use of ICC, the roadway capacity would be dependent on the average time gap setting selected by the drivers. Shorter time gaps would result in a higher capacity than longer gaps. For example, under manual control, traffic flow would approach a capacity of 2,400 vehicles per-hour-per-lane at 55 miles per hour. With an ICC gap setting of 1.0 seconds at 55 mph, a capacity of 2,970 vehicles per hour would result. With a gap setting of 1.4 seconds at 55 mph, the capacity would reach 2,240 vehicles per hour. At 2.0 seconds, the capacity would be only 1,630 vehicles per hour.

Figure 5-3 shows time headway as a function of speed for manual control and the different ICC time gap settings. Note that the ICC concept of constant time gap is different from the pattern exhibited by drivers at different flows and speeds. Based on empirical data, time headway (and gap) decreases continuously as flow rate and speed increases. However, the ICC control algorithms maintain a constant time gap over all speeds.

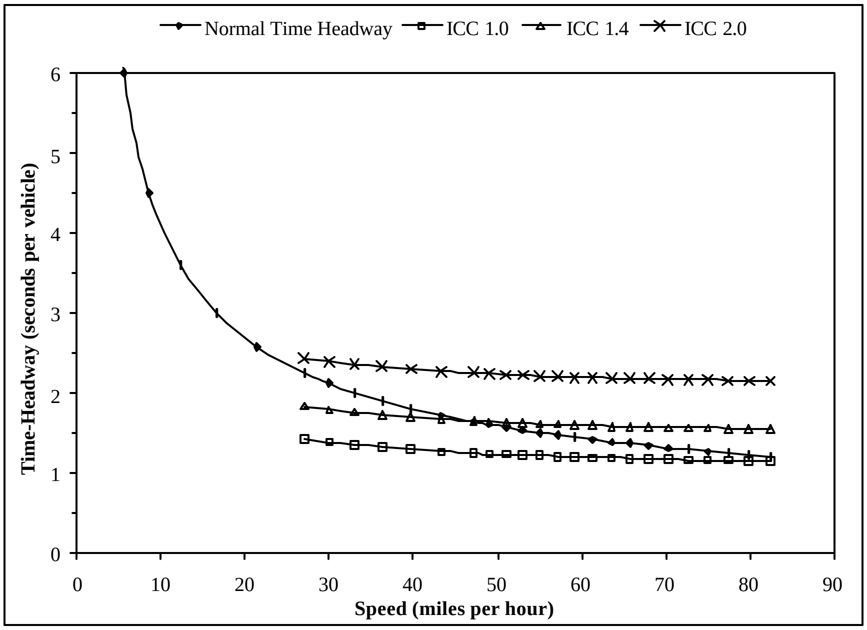

Figure 5-3 Time-Headway Speed Curves, ICC at 100% Market Penetration

Figure 5-4 shows the capacity achieved as a function of speed for manual control and ICC time-headway settings.

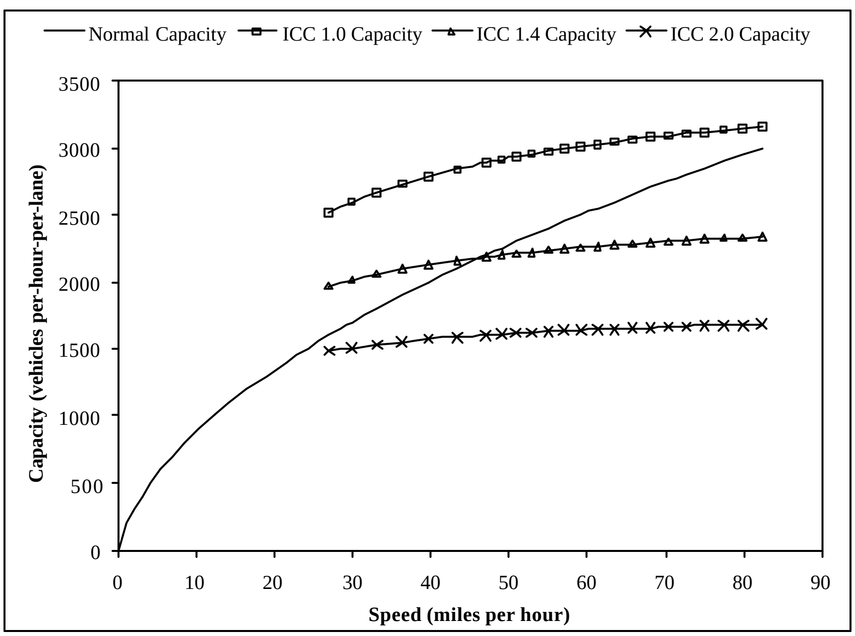

Figure 5-4 Capacity-Speed Curves as a Function of ICC Time-Headway Selection, ICC at 100% Market Penetration

A composite curve can be constructed assuming different levels of ICC market penetration. Figure 5-5 shows composite curves from a number of ICC market penetration scenarios. For example, the first curve, labeled "50% ICC", shows the average capacity that would be achieved at a given speed if 50 percent of vehicles were equipped with ICC. Assuming that drivers that have ICC use it according to the patterns observed in the ICC FOT, the typical driver in an ICC-equipped vehicle will use manual control about a third of the time, and ICC about two thirds of the time. These portions assume freeway driver under uncongested conditions (speeds greater than 50 miles per hour). Selection of headway settings were stratified by age group, and a weighted average of portion of mileage driven under each headway setting was computed based on mileage driven by each age group in the 1995 NPTS results. Both Figures 5-4 and 5-5 show that there is a trade-off speed (approximately 51 miles per hour) where at lower speeds, capacity with ICC is higher than manual control, whereas at higher speeds manual control yields more capacity.

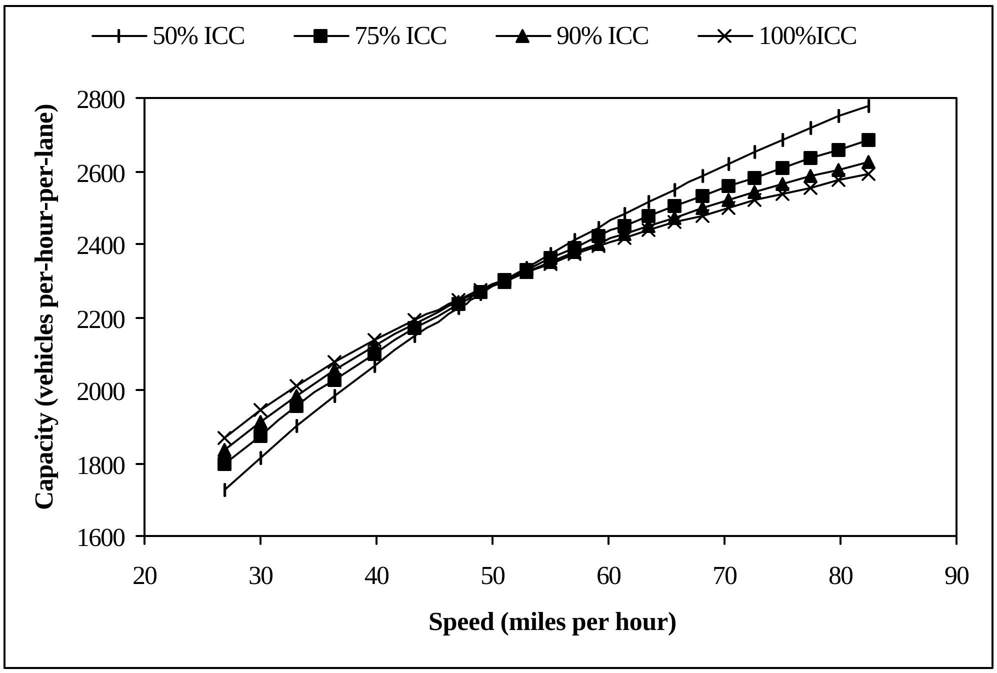

Figure 5-5 Capacity-Speed Curves for Various ICC Market Penetration Levels

5.1.5 Demonstrating the Throughput Benefits of ICC

To demonstrate that ICC would increase throughput, it would be necessary to show that deployment of ICC-like systems would result in (a) higher speeds, (b) shorter time-headways, or (c) both, especially when traffic flows are near capacity. The combination of the higher speed and shorter headway would allow freeways to operate in the "improved flow realm" depicted in Figure 5-2. Taken as a whole, data presented in Chapters 3 and 4 support neither the notion that full deployment of ICC systems would increase speeds, or decrease gaps. However, there are, nonetheless, some trends in the data that suggest that under certain conditions, ICC deployment might increase throughput.

For instance, on Figure 3-45, it was shown that with the 1.0 s headway selected and for most velocities, mean headway was less than it was with manual control. With the 1.4 s and 2.0 seconds time-headway selections, mean time-headway with ICC was longer than it was for manual. As a result, the composite ICC mean time-headway that combined mean headway with the three settings, that took into account the amount of time each setting was used, was longer than manual time-headway. At higher flow rates, if most drivers chose to use the 1.0 s headway when level of service began to decline from B to C (Highway Capacity Manual, 1997), then the ICC system might well increase average throughput. Thus a benefit from shorter time gaps might result from ICC use, if users engage in particular patterns of use. The current study did not identify strong evidence that users would engage in these patterns of use, however.

In Chapter 3 it was also shown that when ICC was used, slightly faster set speeds were selected than were selected with CCC. This small, but statistically reliable, difference could result in faster mean speeds if ICC market penetration, and use, approached 100 percent. This possible outcome could result in increased throughput. Nothing in the FOT data suggested that ICC would result in lower mean speeds, so the higher speed outcome, though it could not be termed likely, is plausible.

Finally, it was found that lane changing appeared to be less frequent when ICC was used. If ICC decreases the amount of lane changing that occurs on roadways that are at capacity, a net increase in throughput can be anticipated. This is because lane changes cause gaps in the lane that is left, and cause drivers upstream in the receiving lane to slow down to regain their desired gap. At capacity, the upstream slowing in the receiving lane is almost inevitable. Although the gap in the lane that is left will eventually close, gap closure is not, on average, as quick to occur. Thus the average net effect of a lane change is a slight decrease in speed in the receiving lane and a slight increase in gap in the losing lane, with a net decrease in throughput the ultimate result.

The FOT was not designed to yield information on throughput effect of ICC deployment, and it did not yield compelling evidence that ICC would effect throughput in either direction. However, if large numbers of drivers chose the 1.0 s time-headway, and if those drivers decreased the amount of lane changing (for which some evidence was provided), then small improvements in throughput on roadways at capacity might result.

The ICC system was not designed to improve throughput. The following section demonstrates an ICC control algorithm that is intended to increase throughput. There is no intent to recommend a headway control algorithm. The discussion that follows is intended to amplify the factors and situations under which ICC deployment could improve throughput.

5.1.6 Alternative Headway Control Algorithms

The constant time gap settings available in the current implementation of ICC would not necessarily result in traffic flow characteristics that increase throughput. Other algorithms for headway control might do a better job increasing throughput than constant time gap algorithms. Figure 5-6 shows a speed versus capacity graph that compares manual control with an algorithm that has a non-linear time gap control function. The selected algorithm has an exponential function that was designed to be asymptotic to a minimum time gap of 1.05 seconds, which equates to a minimum traditional time-headway of 1.2 seconds (i.e., vehicle time headway is accounted for). This algorithm would result in a capacity of 3,000 vehicles per hour per lane, but only at high speeds. Note that the variable time gap function increases lane capacity by 5 to 10 percent within the normal range of speeds encountered on freeways and arterial streets (35 to 65 mi/h, or 56 to 105 km/h). The function achieves this benefit through a small reduction in range; about 10 feet or less. Figure 5-7 shows the vehicle space gap, or range, as a function of speed, for both manual control and the variable time gap function illustrated in Figure 5-6.

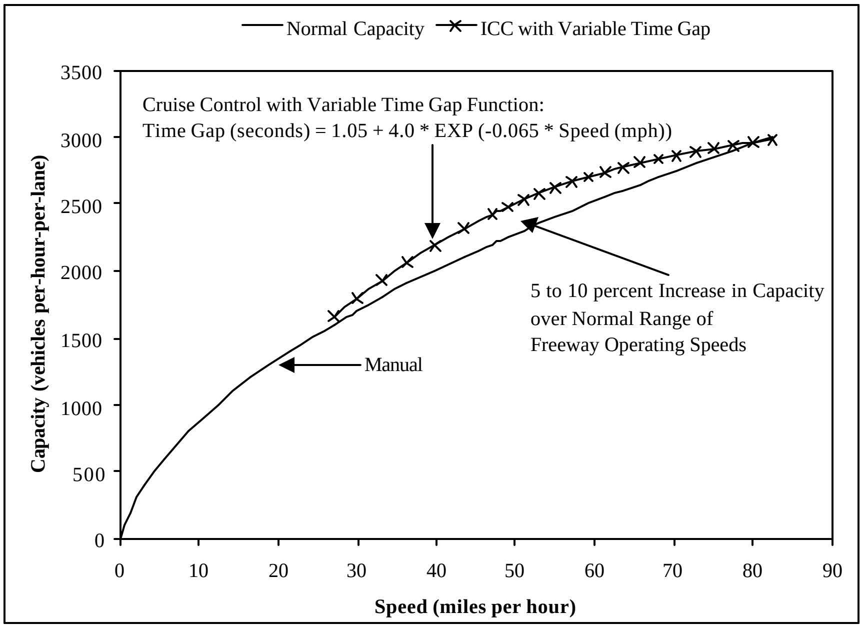

Figure 5-6 Capacity-Speed Curves Illustrating Potential Benefit from an Alternative Headway Control Algorithm

A variable gap benefit could only be achieved if all ICC drivers were using the same variable time gap function. The function demonstrated above would be classified as an "aggressive" control function analogous to the current 1.0 second ICC setting. Like the fixed time gap setting, different variable time gap settings could be selected for different situations. Rather than selecting a fixed value of time gap, the driver might select an "aggressive", "normal" or "relaxed" headway setting that would adjust the shape of a time-gap curve. An aggressive setting would be most appropriate for experienced commuters on well-known routes. A normal setting might be appropriate for off-peak urban driving situations where flow rates were moderately high. A relaxed setting might be appropriate for situations such as recreational travel. Just as freeways achieve different capacity flow rates under manual driving conditions based on the mix of aggressive, average, and less aggressive drivers, variable gap control functions could seek to increase throughput for a mix of drivers.

5.1.7 Traffic Flow Summary

Under certain conditions of short time-headway settings (e.g., 1.0 second) and high speeds, ICC systems could improve roadway capacity. Longer time-headway settings (e.g., 2.0 seconds) could reduce roadway capacity. Alternative, non-linear time-headway control algorithms could improve roadway capacity beyond that of the tested system. Also, alternative algorithms could reduce the impact on traffic flows of instabilities caused by multiple ICC equipped vehicles tracking one another.

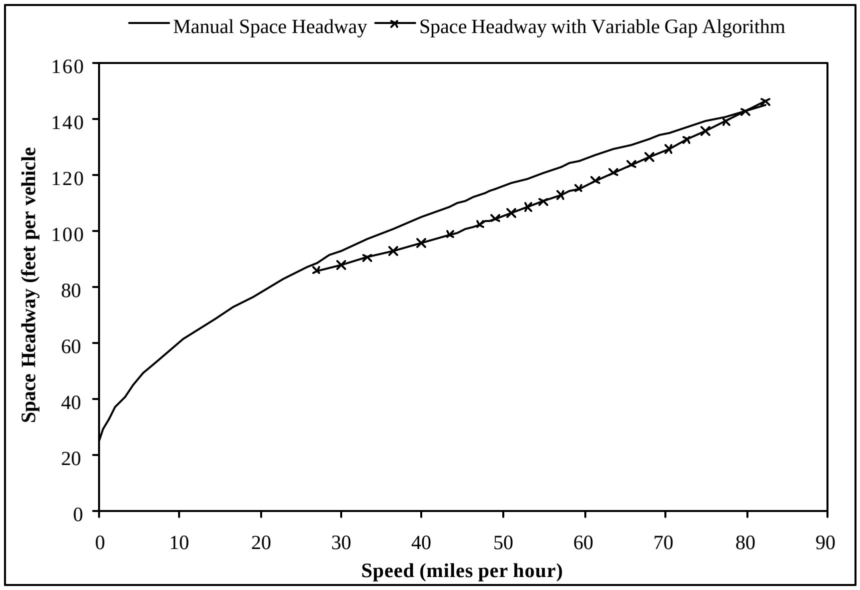

Figure 5-7 Space-Headway Speed Curves for Manual Control and an Alternative Variable Gap Algorithm

Appendix M, *Intelligent Cruise Control Systems and Traffic Flow Behavior* provides a further examination of the ICC impacts on traffic flow including a discussion on the potential turbulence or speed drop effects at the upstream end of a disturbance such as a lane change or ramp egress. A simulation is developed to provide space time representation and results are presented for different levels of market penetration.

5.2 Fuel Consumption and Emissions

It was hypothesized that ICC might result in fuel savings and emissions reductions, compared to manual control, because the ICC system could exercise finer throttle control, and obviate the need for larger corrections. Figure 5-8 shows percent of throttle for representative samples of driving for one ICC participant. Both samples are from cases where the host vehicle driver was following another vehicle on the freeway. It can be seen that the fluctuations in throttle setting were indeed larger in manual mode than in ICC (ICC had a 1.0 second time headway setting). This characteristic of wider fluctuations in throttle in manual than in ICC, is consistent with the finding, reported in Figure 3-55, of greater speed variability in manual mode than in ICC.

To more directly test for fuel savings and emissions reductions, the acceleration and velocity data from 108 drivers were applied, on a second by second basis, to the fuel and emissions equations presented in Chapter 2. The resultant estimates of fuel consumed and gases emitted were then summed for each driver as a function of cruise control mode, road class, and velocity regime. Velocity regimes were defined as 5 mi/h intervals that began at 25 mi/h (40.3 km/h), the minimum speed at which ICC could remain active. The focus here is on freeways in the speed range between 55 and 70 mi/h (88.5 and 112.7 km/h). Because benefits achieved with ICC were hypothesized to be the result of reduced speed variability, and because on freeways it appeared that below 55 mi/h manual mode speed was more variable due to congestion, speeds below 55 mi/h were not examined closely. Also, there was very little ICC driving below 55 mi/h making appropriate comparisons of manual and ICC below 55 mi/h questionable.

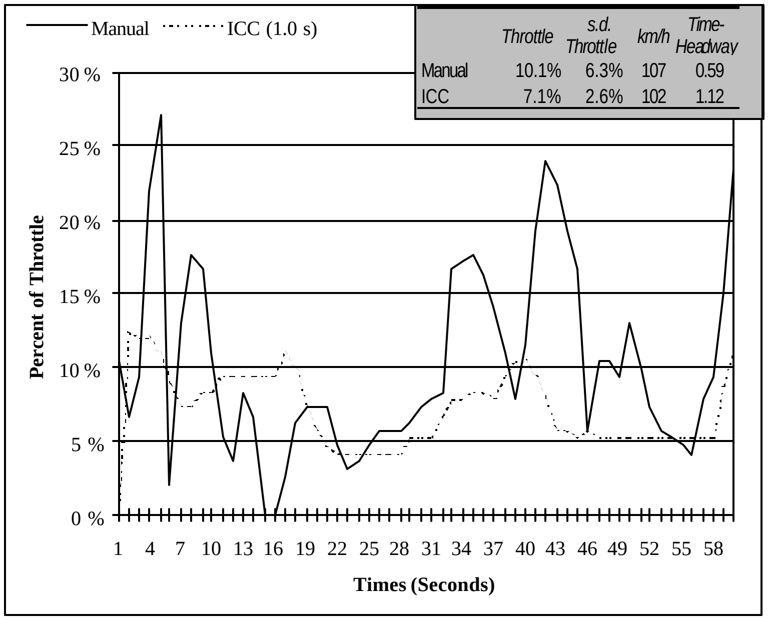

Figure 5-8 Representative Sample of Percent of Throttle for 60 Seconds of Driving in ICC and Manual Modes

5.2.1 Fuel Consumption Results

As can be seen in Figure 5-9, the fuel model did project fuel savings with ICC relative to manual driving. The effect of velocity on fuel consumption over this small range of speeds was statistically reliable, F (1, 52) = 357.7, $p < 0.001$. However, higher order effects could not be detected statistically due to this limited range of speeds. Note that the results in Figure 5-9 are based on the 58 drivers who routinely traveled among all the different speed bins, and used all three driving modes. The cruise mode effect was also reliable, F (2, 104) = 8.4, $p < 0.001$. Although the difference between CCC and ICC was not statistically reliable, it was surprising, as it was anticipated that CCC would yield higher fuel economy than ICC, because ICC can adjust the throttle to maintain a fixed time-headway, whereas CCC does not. Although this finding was not thoroughly investigated, preliminary analyses suggest that there was slightly more acceleration with CCC than ICC. This could have been the result of drivers overriding the throttle more often with CCC, or it could have been the result of differences in the throttle command implementation by Chrysler (for CCC) and UMTRI (for ICC).

There were no age or previous cruise control use effects on projected fuel consumption. The mode effect was similar across velocity bins. The mode effects were not statistically significant between velocity bins.

The fuel consumption model results in this study therefore suggest that wide-spread implementation of ICC-like systems would result in substantial fuel savings because, whereas both CCC and ICC conserve fuel relative to manual speed control, ICC would be used more often, and by more drivers than CCC.

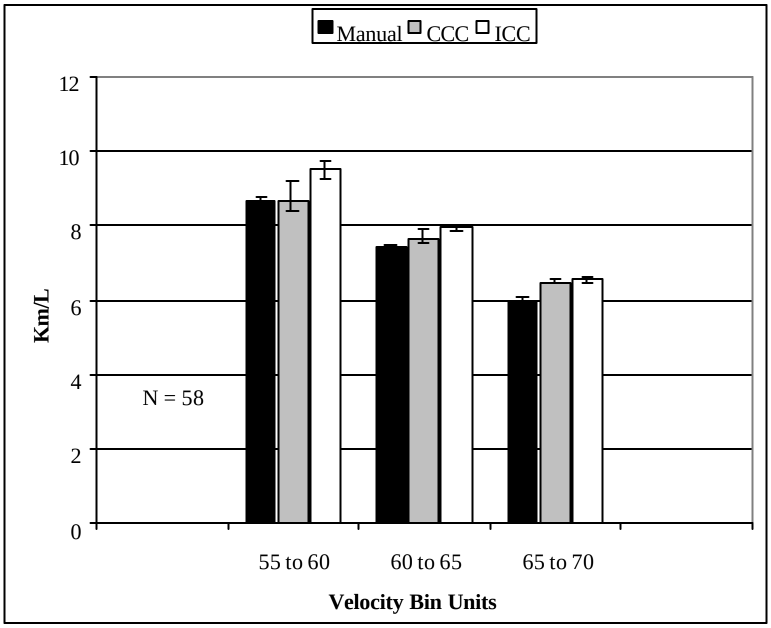

Figure 5-9 Estimated Fuel Consumption as a Function of Cruise Control Mode and Velocity Regime (10 km/L ~ 23.5 mpg)

Above 70 mi/h velocity overwhelmed acceleration in the model's determination of fuel consumption. Below 55 mi/h acceleration had a greater effect, but the number of observations, particularly in the CCC and ICC velocity regimes, was quite limited. Figure 5-10 shows the means and two-standard errors for 5 mi/h velocity regimes from 30 through 75 mi/h. Unlike Figure 5-9, which includes only drivers who had observations in each mode and velocity classification, in Figure 3-10 each driver had to have driven in each mode within a particular velocity regime. It can be seen that the ICC fuel savings benefit holds across the entire velocity range. Although the benefits from ICC appear larger at the lowest velocities, the amount of ICC use at the low velocities was limited. Thus the major benefit, on freeways, would come from driving at velocities above 55 mi/h, where the number of kilometers of use would outweigh the smaller per kilometer benefit.

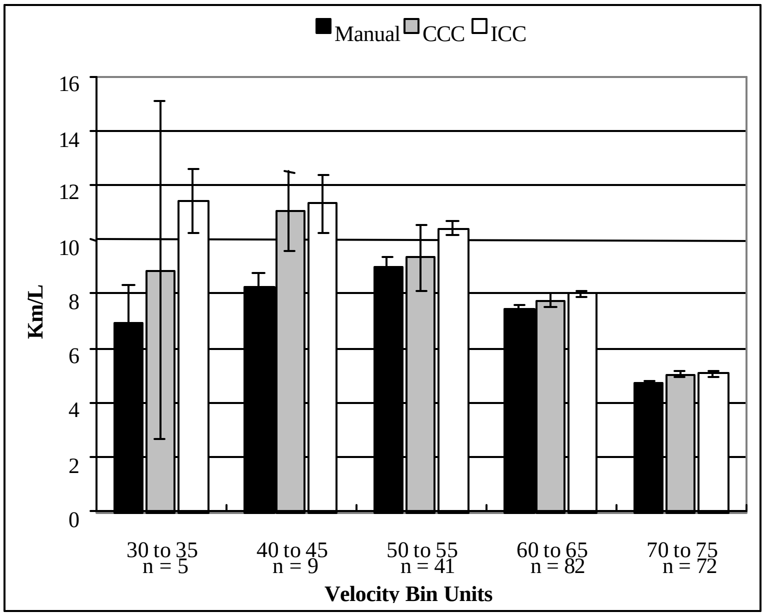

Figure 5-10 Selected Fuel Consumption Model Results Across the Range of Velocities (in mph) Examined (n=number of drivers represented)

5.2.2 Emissions Results

The emissions results are similar to those for fuel savings. ICC resulted in fewer emissions of nitrous oxide, hydrocarbon, and carbon monoxide relative to manual control, and emissions increased with speed. For all three gases, the statistical analyses were performed on the natural log of the emissions computed from the model. (The model's output was in natural log units, but the model outputs had been transformed back to the original units [milligrams/km] prior to being stored in the evaluation database.) The log transformation was used to bring the sample distributions to a form that more closely fit the assumption of the analysis of variance model, i.e., that the means were from a normally distributed population.

The model results for carbon monoxide emissions are shown in Figure 5-11. The mode effect was robust, $F(2, 104) = 10.2$, $p < 0.001$, with cruise control yielding clearly lower emissions. At the higher velocities the ICC benefit over manual driving increases. The velocity effect was substantial as well, $F(2, 104) = 1355.1$, $p < 0.001$, and accounted for 96 percent (by h^2) of the variance in the statistical model.

An unexpected finding was that drivers who said they were cruise control users prior to entering the study had higher CO emissions than those who said they did not use cruise control. This is shown in Figure 5-12. Prior cruise users were shown in Chapter 3 to choose, on average, a shorter headway and a faster speed than nonusers. The headway preference in particular is a likely source of the CO finding, as a shorter headway would likely yield more acceleration commands for control than a longer headway. Speed could also have been a factor, but because these data were already segregated into speed regimes, mean speed differences within bins were small.

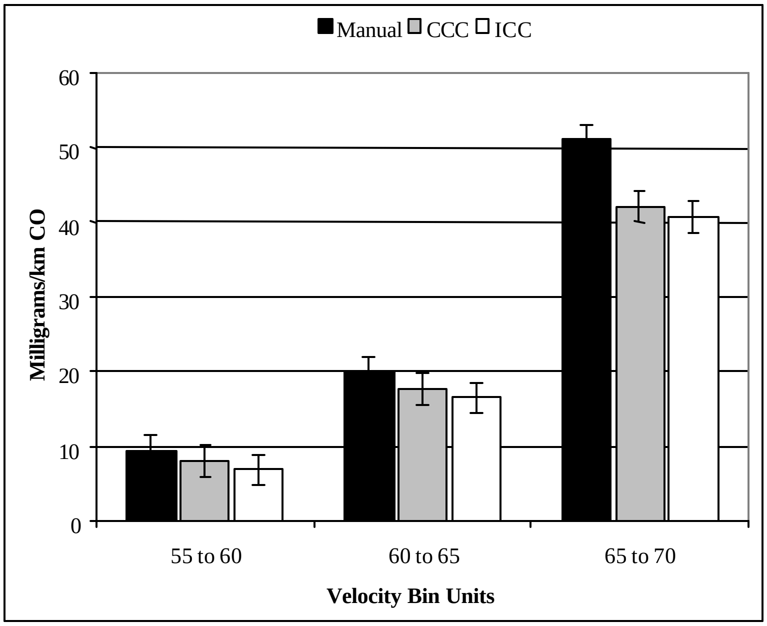

Figure 5-11 Estimated Milligrams per Kilometer of Carbon Monoxide as a Function of Cruise Mode and Velocity Regime

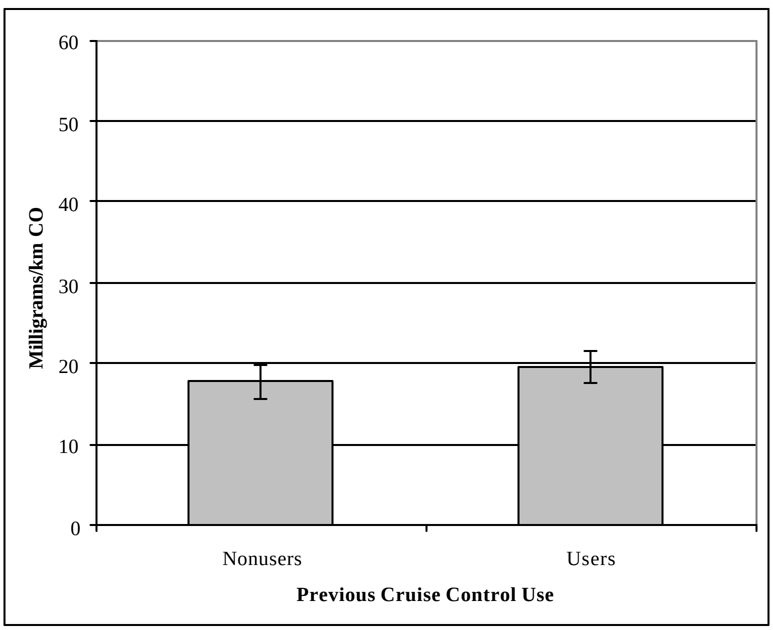

Figure 5-12 Projected Carbon Monoxide Emissions as a Function of Previous Cruise Control Use

The primary NO_x findings are presented in Figure 5-13. Again the mode effect, F (2, 104) = 6.5, $p < 0.01$, and velocity effect, F (2, 104) = 905.9, $p < 0.001$, were statistically reliable. There were no other significant effects. It can be seen that the NO_x emissions increase considerably with velocity, they decrease with ICC driving, and the ICC benefit over manual driving increases with velocity.

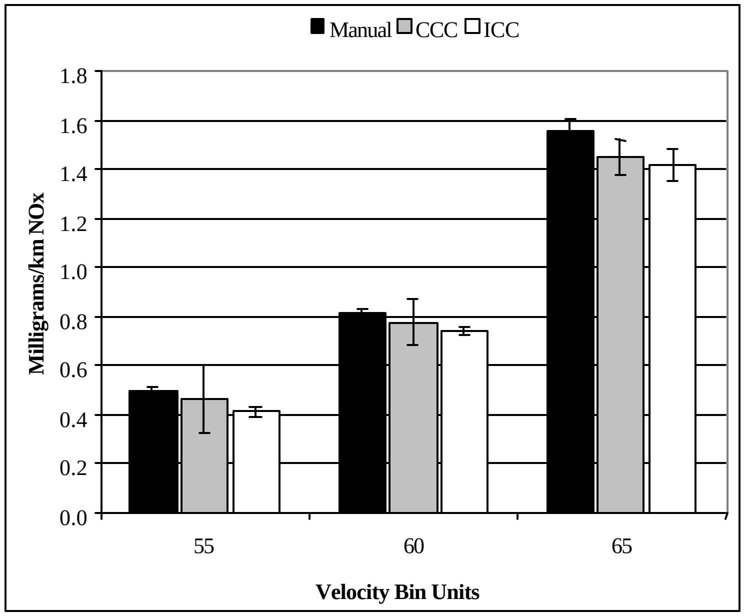

Figure 5-13 Estimated Milligrams per Kilometer of Nitrogen Oxide as a Function of Cruise Mode and Velocity Regime.

Projected hydrocarbon emissions are shown in Figure 5-14. As with NO_x, HC emissions increase with velocity, they decrease with ICC driving and the ICC benefit over manual driving increases along with the overall velocity . The effects of mode, F (2, 104) = 9.4, $p < 0.001$, and velocity, F (2, 104) = 1094.0, $p < 0.001$, were statistically reliable. There were no other main effects or interactions.

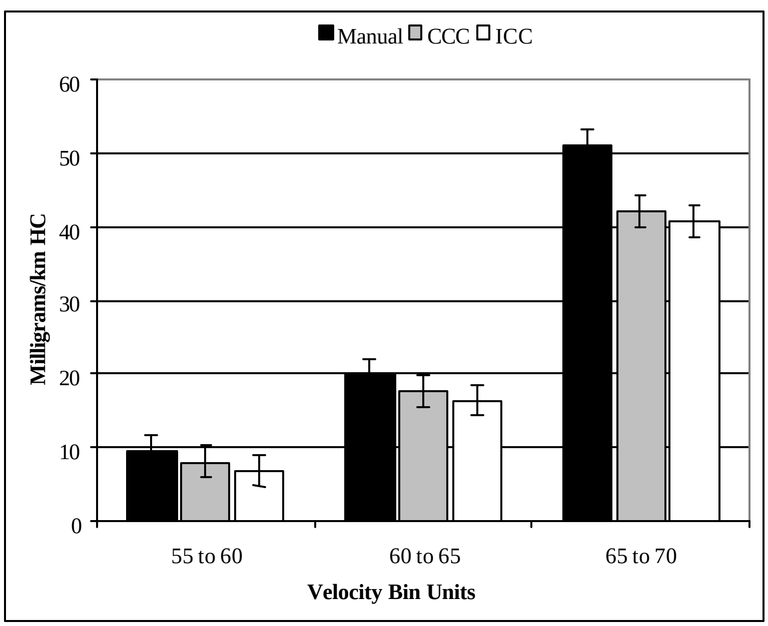

Figure 5-14 Estimated Milligrams per Kilometer of Hydrocarbon as a Function of Cruise Mode and Velocity Regime.

5.2.3 Fuel Consumption and Emissions Summary

The FOT data suggest that because ICC reduces the degree of acceleration relative to manual driving, and because ICC would be used more than CCC, deployment of ICC systems will result in increased fuel efficiency and decreased emissions. This benefit might be offset somewhat, if ICC also increased overall roadway speed (i.e., a large throughput benefit were attained). But since the fuel and emissions savings would be attained at all levels of service, not just at the point in traffic flow where capacity is reached, a net fuel consumption and emissions benefit would likely be derived even with the throughput benefit.

5.3 ICC Cost Analysis

The ICC cost analysis focuses on a comparative analysis between the development of Anti-Lock Braking Systems (ABS) and the potential development of ICC systems. The basis for this analysis is the anticipation in the automotive electronics community that the development of ICC systems will follow a path similar to that of ABS.

> *Our projections are that once the [ICC] technology is accepted at the high end of the market, then it will follow a similar development and acceptance within the market as ABS*
>
> — Nick Ford, Lucas, U.K.(Martin, 1995).

5.3.1 Introduction

This comparative analysis focuses on cost reductions over time that result from increases in production and improvements in system technology. The analysis first quantifies both the "production learning curve" and ABS technology improvements that have led to cost reductions over time. Second, the application of these results is used to develop an analogy with the potential or forecasted development of ICC systems.

The results of this analysis are cost-quantity curves that show the potential costs of ICC systems over time and allow for an evaluation of manufacturer ICC cost projections. Moreover, these curves are then compared to "Willingness to Pay" results from the ICC user acceptance study.

The technical approach for this study is outlined below in Figure 5-15. The steps shown also serve as the organization for this section.

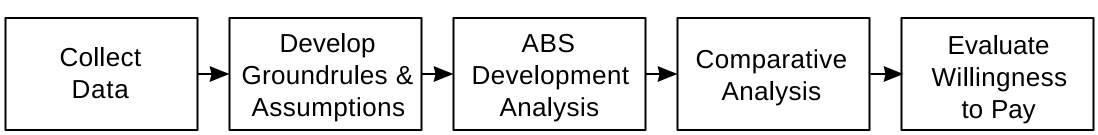

Figure 5-15 Study Technical Approach

5.3.2 Data Collection

There were two cost data collection goals. First, reports and other historical data on the development of ABS were sought for the period from the late 1960's through the present. Attainment of this goal provided cost data, technical descriptions, and production quantities of ABS systems.

Second, data were sought on the current (i.e., early) development period for ICC systems from the late 1980's through the present. Attainment of this goal provided cost data, technical descriptions, and production quantities of ICC systems available today or planned in the near future.

The data collection effort centered on research reports found in the UMTRI Library. Additional material was gathered from the Internet and research reports obtained from the library at the University of California at San Diego.

The results of data collection proved adequate to support this analysis. Cost projections for future ICC systems should be viewed as preliminary price quote projections from automotive electronics suppliers.

5.3.3 Ground Rules and Assumptions

Several ground rules and assumptions were necessary to (1) bound the cost analysis by limiting and clarifying the scope, and (2) establish the baseline conditions. The following ground rules and assumptions were established for this analysis:

- All costs were normalized to U.S. 1997 Dollars. The cost model inflation factors are given in Appendix N, *Cost Model Inflation Factors*.
- "Costs" were defined as the unit cost to consumers for ICC as an option on a new automobile (i.e., the dealer option price).
- It was assumed that conventional cruise control is incorporated in the ICC package (i.e., ICC is not installed "on top" of CCC).
- Where sources treated ICC costs as an add-on to CCC, $190, the standard option price for CCC (Martin, 1995), was added to normalize the ICC total system price.

5.3.4 ABS Development Analysis

The ABS development analysis was performed in three phases: (1) analysis of the first generation ABS systems, (2) analysis of second generation ABS systems, and (3) development of a parametric cost model for both first and second generation systems.

5.3.4.1 First Generation ABS Systems Analysis Early research on ABS systems for automobile applications began in the U.S. and Europe in the 1950's. Test and development programs commenced in the late 1960's. Early test and development programs typically consisted of one-channel vacuum powered ABS systems. By the early to middle 1970's, auto makers and suppliers were poised to introduce the multi-channel, multi-wheel, first generation ABS systems.

Table 5-2 summarizes the 1971 Chrysler/Bendix "Sure Brake" ABS. The system was the first true 4-wheel ABS system introduced into an automobile in the United States. Chrysler produced the system in limited numbers as a prototype production ABS system for the U.S. Market. While a technical success, the system generated little consumer interest. Cost and production data were not available. This system should be considered an early first generation system that validated the technologies necessary for the introduction of ABS systems.

Table 5-3 provides a technical and development summary of the 1972 Teldix/ Mercedes ABS. This system, which was developed for an extensive ABS test program conducted by Robert Bosch GmbH and Mercedes, was the first ABS system to have separate skid control for all four wheels. While not a production system, the lessons learned from this development and test program paved the way for European introduction, later in the decade, of first generation ABS systems.

Table 5-2 Chrysler/Bendix 1971 "Sure Brake" ABS (Douglas and Schafer, 1971; Dalin, 1972)

- 3 Control Channels, 4-wheel anti-skid system
- Front wheels independently controlled; rear wheels treated as pair
- Each control channel contains a pressure modulator, analog computer, and an inductive sensor
- Vacuum powered actuators
- Required specially designed brake system
- Offered as option on 1971 Chrysler Imperial (low volume luxury vehicles)
- Produced in very low volumes; little consumer interest shown from U.S. market
- Preliminary Research began in 1957; production design began in 1966

Table 5-3 Teldix/Mercedes 1972 ABS (Dalin, 1992)

- 4 Control Channels, 4-wheel anti-skid system
- All 4 wheels individually controlled
- Each control channel contains a pressure modulator, an analog computer, and an inductive sensor
- Hydraulic powered actuators
- Required specially designed dual circuit brake system master cylinder
- Test System only; no significant production quantities; no cost data available

Table 5-4 provides a technical and development summary of the 1978 Bosch ABS System for Mercedes cars. This system was based on the technical lessons learned from the development and test program of the 1972 Teldix/Mercedes ABS, and also incorporated a simplified 3 control channel, 4-wheel system similar to that used on the 1971 Chrysler Sure-Break ABS. This system was also one of the first ABS systems that could be integrated with an existing hydraulic brake system. This system was the predominate European ABS system of the early 1980's. It was available as an option on Mercedes luxury cars. By 1985, 500,000 of these systems had been introduced with the average cost $1742. This system may be considered the most successful first generation ABS.

Table 5-4 Bosch 1978 ABS System for Mercedes Cars (Dalin, 1992; Newton and Riddy, 1985)

- 3 Control Channels, 4-wheel anti-skid system
- Front wheels independently controlled; rear wheels treated as pair
- Each control channel contains a pressure modulator, and an inductive sensor
- System controlled by a single digital computer
- Hydraulic powered actuators integrated with brake system
- Add-on to existing brake system
- Offered as option on Mercedes luxury vehicles from 1978-1985
- Produced in moderate quantities as an option for most Mercedes luxury vehicles; 500,000 vehicles produced with the system by 1985
- Average cost in 1984 of European ABS systems such as this was $1742 (97$)

It is clear that the 1978 Bosch ABS system is the most applicable base for a generic first generation ABS model. This system was the only successful, and extensively produced, first generation ABS. It is important to note that U.S. first generation systems, such as the 1971 Chrysler Sure-Break, did not succeed in U.S. market. Only the 1978 Bosch ABS system deployed on Mercedes cars in Europe achieved market success, and this was only on relatively moderate production runs that supported limited availability on high-end luxury cars.

The first generation ABS model, derived from the 1978 Bosch ABS system, is shown in Table 5-5. The average cost of $1742 and the annual production of 62,500 units were used as inputs to the ABS parametric cost model that is detailed in section 5.3.4.3.

Table 5-5 First Generation ABS Model

- 3 Control Channels, 4-wheel antilock system
- Front wheels independently controlled; rear wheels treated as pair
- Each control channel contains a pressure modulator, and an inductive sensor
- System controlled by a single digital computer
- Hydraulic powered actuators integrated with brake system
- Add-on to existing brake system
- Production: In low-moderate quantities as an option for luxury vehicles; assume production runs of 62,500 per year or system version (consistent with 500K quantity of total production of Bosch ABS System from 1978-1985)
- Cost to Consumer: $1742 (97$)

5.3.4.2 Second Generation ABS Systems Analysis By the mid-1980s, the basic technologies of ABS had been proven in Europe. Both European and U.S. suppliers began to examine steps to significantly reduce cost, without sacrificing performance, so that ABS systems would be affordable for the wider consumer market that spans the range of cars and light trucks. Two primary elements supported this goal: (1) improvements in control technology and software, and (2) increased integration and modularity of ABS components.

Moreover, it was anticipated that implementation of these elements would reduce costs to the extent that demand would increase, which in turn would reduce costs further as a result of production learning and economies of scale. In other words, through increased mass production, manufacturing costs per unit were expected to go down.

The promise of technical improvements and cost reductions was first realized in 1985 with the introduction of the Lucas Girling Antilock System. This ABS, which is detailed in Table 5-6, provided advanced control algorithms and an advanced microprocessor control system that enabled the system to work with only two control channels, but preserved the capability of more expensive three-channel systems. In addition, the increased integration of sub-systems allowed for significant production cost reductions.

Table 5-6 Lucas Girling 1985 Antilock System (Riddy and Edwards, 1987)

- 2 Control Channels, 4-wheel ABS system with capabilities of 3 channel systems
- Front wheels independently controlled; rear wheels controlled by system logic
- Each control channel contains a compact integrated unit containing sensor, controller, pressure modulator, and power source
- Advanced microprocessor control system
- Simplified hydraulic connectivity to existing brake system
- Offered as option on Ford-Europe Escort and Orion Models
- Produced in high volumes
- Cost: Unknown

The 1985 Lucas Girling Antilock System became the first mass-produced low-cost ABS system that could control all four wheels. Subsequently, it became the first mass produced ABS for mid-size and economy class front-wheel drive cars. This system formed the basis for second generation ABS systems. A large number of second generation ABS systems, based on the advancements reflected in the 1985 Lucas Girling Antilock System, have been produced.

Cost data was not available for the 1985 Lucas Girling Antilock System. To develop costs inputs to a second generation ABS model, cost data were collected for the representative set of recent ABS systems that are listed in Table 5-7.

Table 5-7 Costs of Recent Second Generation ABS Systems (Wards Automotive World, 1995)

Manufacturer	*Application*	*Price Range*
Bosch	Small Front-Wheel Drive Cars	\$565 - \$599
Bosch	Medium Front-Wheel Drive Cars	\$599 - \$649
Bendix	Small Front-Wheel Drive Cars	\$565
Bendix	Medium Front-Wheel Drive Cars	\$565 - \$699
Teves	Small/Medium Front-Wheel Drive Cars	\$565
Teves	Large Front-Wheel Drive Cars	\$665
Delco	Small Front-Wheel Drive Cars	\$565 - \$595
Delco	Medium Front-Wheel Drive Cars	\$450

The above systems have become standard options on many vehicles. Worldwide production of ABS systems per year is now over ten million.

The derived second generation ABS model is presented in Table 5-8. The average cost of $596 and the annual production of 500,000 units served as input to the ABS parametric cost model that is described next.

Table 5-8 Derived Second Generation ABS Model

- 2 Control Channels, 4-wheel antilock system
- Front wheels independently controlled; rear wheels controlled by system logic
- Each control channel contains a compact integrated unit containing sensor, controller, pressure modulator, and power source
- Advanced microprocessor control system
- Simplified hydraulic connectivity to existing brake system
- Modular design to allow for use on multiple vehicle types
- Production: In high production quantities as an option for many small and mid-size cars; assume production runs of 500,000 per year of system version (consistent with quantity of total production of over 10 million units per year worldwide)
- Cost to Consumer: $596 (97$) (based on average of current small and mid-size ABS systems)

5.3.4.3 ABS Production/Technology Parametric Cost Model A parametric ABS cost model was developed by generating standard cost-quantity production learning curves for both the first and second generation ABS models based on their respective average unit cost and corresponding production quantity inputs. For the slope of the production learning curve, the standard auto suppliers learning curve slope of 84% was utilized (Ervin, 1978).

Based on the percentage difference between the first- and second-generation learning curves, a "Technology Improvement" factor was calculated. This factor provided a measure of the cost reduction attributable to technology lessons learned.

The following equation presents the standard average unit cost production learning curve based on a slope of 84%:

$$U = T1 \times Q^{\frac{\log(0.84)}{\log(2)}} = T1 \times Q^{-0.2515}$$

where: U = Average Unit Cost
Q = Quantity Produced
T1 = Theoretical First Unit Production Cost.

From the above equation, the Theoretical First Unit Production Cost (T1) can be derived for both the first and second generation ABS systems:

$$T1_{1st} = \frac{U}{Q^{-0.2515}} = \frac{\$1,742}{62500^{-0.2515}} = \$28,016$$

$$T1_{2nd} = \frac{U}{Q^{-0.2515}} = \frac{\$596}{500000^{-0.2515}} = \$16,172$$

The derived T1 values are then plugged back into the standard average unit cost production learning curve equations to generate the final standard cost equations for first and second generation systems:

$$U_{1st} = \$28,016 \times Q^{-0.2515}$$

$$U_{2nd} = \$16,172 \times Q^{-0.2515}$$

These equations are graphed in Figure 5-16, and form the basis for the ABS cost model. The technology improvement is the percentage difference between the two curves. This is developed as a factor from the ratio of derived T1's of second generation versus first generation ABS:

$$F_{Tech} = \frac{T1_{2nd}}{T1_{1st}} = \frac{\$16,172}{\$28,016} = 0.577$$

Thus, for a given production quantity, a 42% reduction in cost between first and second generation ABS can be attributed to advances in second generation ABS technology. Improvements included control technology, software, and increased integration and modularity of ABS components.

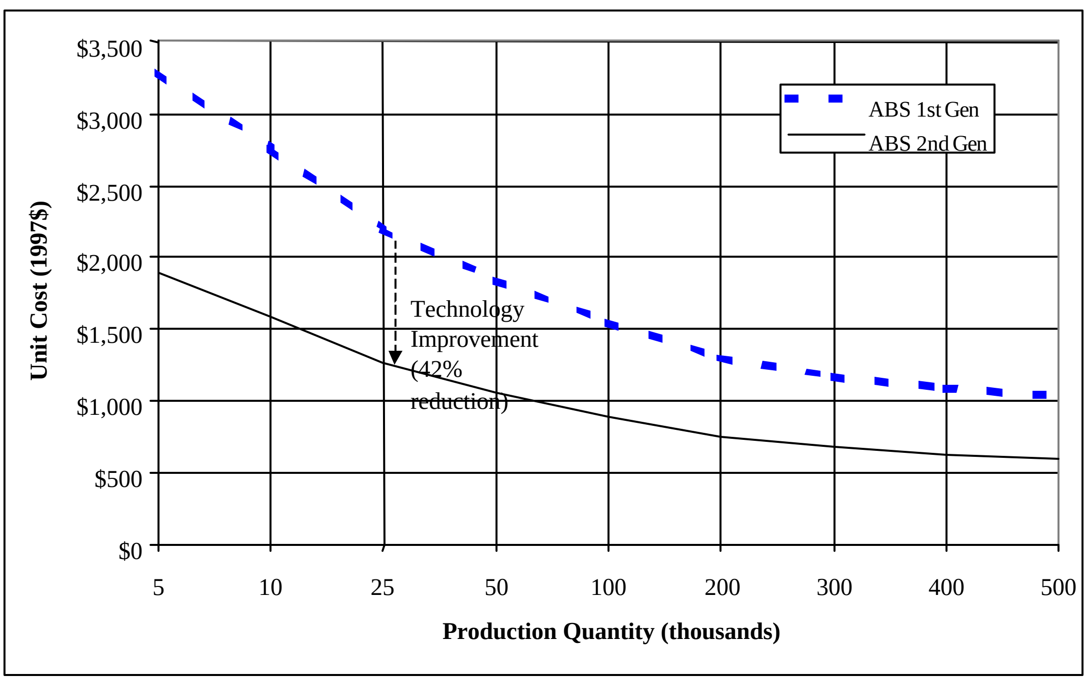

Figure 5-16 ABS Cost Model

Elements of this model can be used as an analogy to ICC cost reductions over time. Specifically:

1. The production learning curve of 84% can be applied to ICC estimates
2. The technology improvement factor of 0.58 (42% reduction) can be applied to ICC first generation estimates to evaluate potential ICC second generation costs.

5.3.5 ABS-ICC Comparative Analysis

In this section we first review the available data on ICC systems. These data are then evaluated against analogous data from ABS systems.

5.3.5.1 Comparative Analysis The first step in the comparative analysis was to generate ICC system standard cost-quantity production learning curves in a manner similar to that used to generate the ABS production learning curves. The standard auto supplier learning curve slope of 84% was used.

For the 1995 Mitsubishi "Preview Distance Control" ICC System: T1 = $31,443 (for Q=10,000 and U=$3100) (Q margin of error = -5000, +10,000)[1]

$$U = \$31,443 \times Q^{-0.2515}.$$

For the 1998/1999 Mercedes/Bosch ICC System: T1 = $30,428 (for Q=10,000 and U=$3000) (Q margin of error = -5000, +10,000)[2]

$$U = \$30,428 \times Q^{-0.2515}.$$

For the Late 90s/Early 2000's Lucas ICC System: T1 = $3,077 (for Q=100,000 and U=$170)[3]

$$U = \$,3077 \times Q^{-0.2515} + \$190$$

($190 added to include CCC components).

For the Late 90s/Early 2000's Leica ICC system: T1 = $6,783 (for Q=500,000 and U=$250)[4]

$$U = \$6,783 \times Q^{-0.2515} + \$190$$

[1] The quantity (Q) and unit price (U) data for Mitsubishi were obtained from were obtained from "Collision Warning Systems in the U.S. and Japan," on the ITS America website (http://www.itsq.org/facts/factcoll.html).

[2] The quantity (Q) and unit price (U) data for Mercedes/Bosch were obtained from were obtained from David Sedgwick's "Consider Adaptive Cruise Control," *Automotive News*, March 17, 1997.

[3] The quantity (Q) and unit price (U) data for Lucas were obtained from were obtained from "Lucas Eyes AICC Market, Expects Vehicle Control Product Launches in 2000," *The Intelligent Highway*, December 23, 1996.

[4] The quantity (Q) and unit price (U) estimated data provided by Leica as project partner.

($190 added to include CCC components).

The cost-quantity production learning-curves that resulted are shown in Figure 5-17.

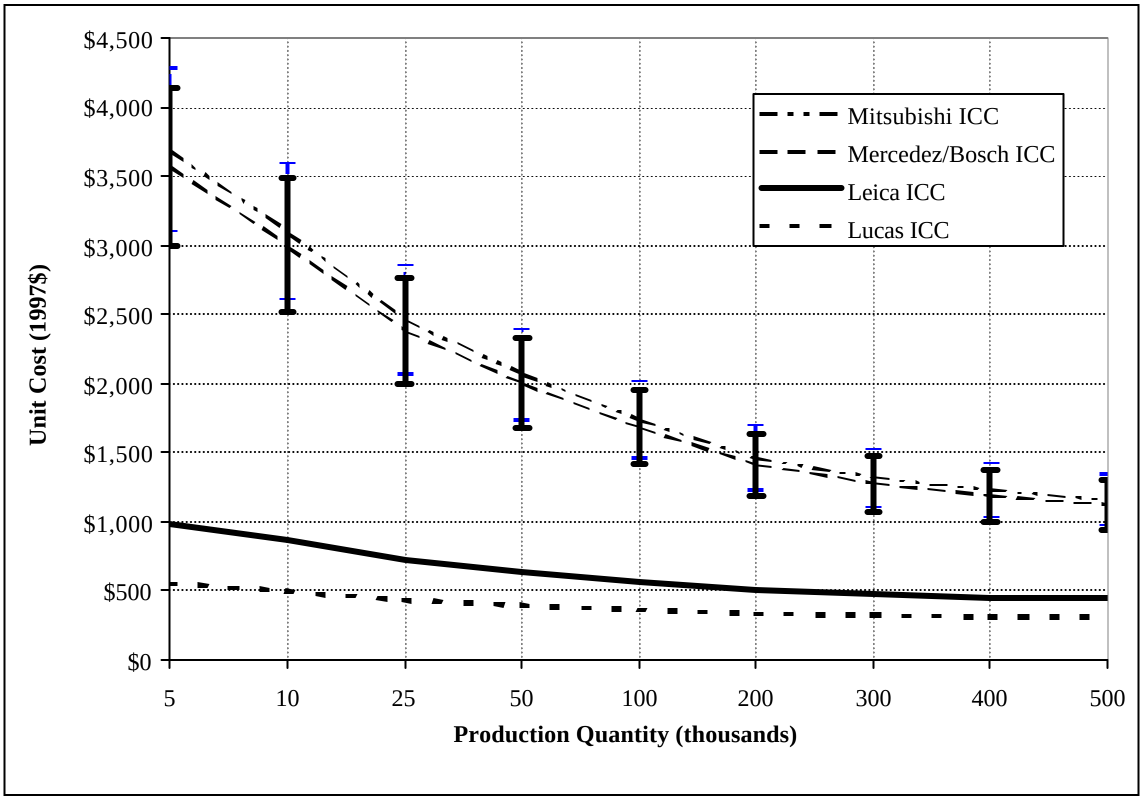

Figure 5-17 Application of the ABS Production Learning Curve to ICC Systems

There was major difference between the Mitsubishi and Mercedes/Bosch cost curves compared to the Lucas and Leica cost curves. The Lucas and Leica projections were about 27% to 38% of the value of the Mitsubishi and Mercedes/Bosch projections. In mass production (500,000 units), the projected average cost for a Mitsubishi/Mercedes-Bosch ICC system was about $1140, whereas the average projection for a Lucas/Leica ICC system was about $303/$440.

One interpretation of these results is that the Lucas and Leica ICC systems may be considered second or later generation systems, whereas the Mitsubishi and Mercedes/Bosch systems may be considered first generation systems. This promise is supported by the following:

1. The Mitsubishi and Mercedes/Bosch systems are being introduced several years before the Lucas and Leica systems. This is consistent with ABS development, in which the most successful first generation ABS was introduced seven years before the initial second generation system. Moreover, the Lucas and Leica systems will be able to build upon the technologies showcased in the Misubishi and Mercedes/Bosch systems.

2. The Mitsubishi and Mercedes/Bosch systems are, or will be, deployed on high-end luxury cars, much as the first generation ABS systems were deployed.

3. The Lucas system suggests a lower-cost solid-state radar sensor in mass production of 100,000 units per year, while the Leica system suggests a lower cost technology (IR Sensor). Additionally, the Lucas system incorporates the addition of brake control (additional technical performance at reduced cost). Therefore, the use of advanced technologies at lower cost is analogous to the use of lower cost technologies in second generation ABS systems.

Acceptance of this premise leads to the comparison of the Lucas and Leica cost estimate curves with an ABS-derived second generation ICC cost curves. These curves can be derived by applying the ABS technology factor (44% reduction in cost due to technology improvements in the second generation) to an average of the Mitsubishi and Mercedes/Bosch curve. The plot that results is shown in Figure 5-18. Again, the justification for applying the ABS Technology Factor is based on the anticipation that ICC systems will be following a similar development path to that of ABS.

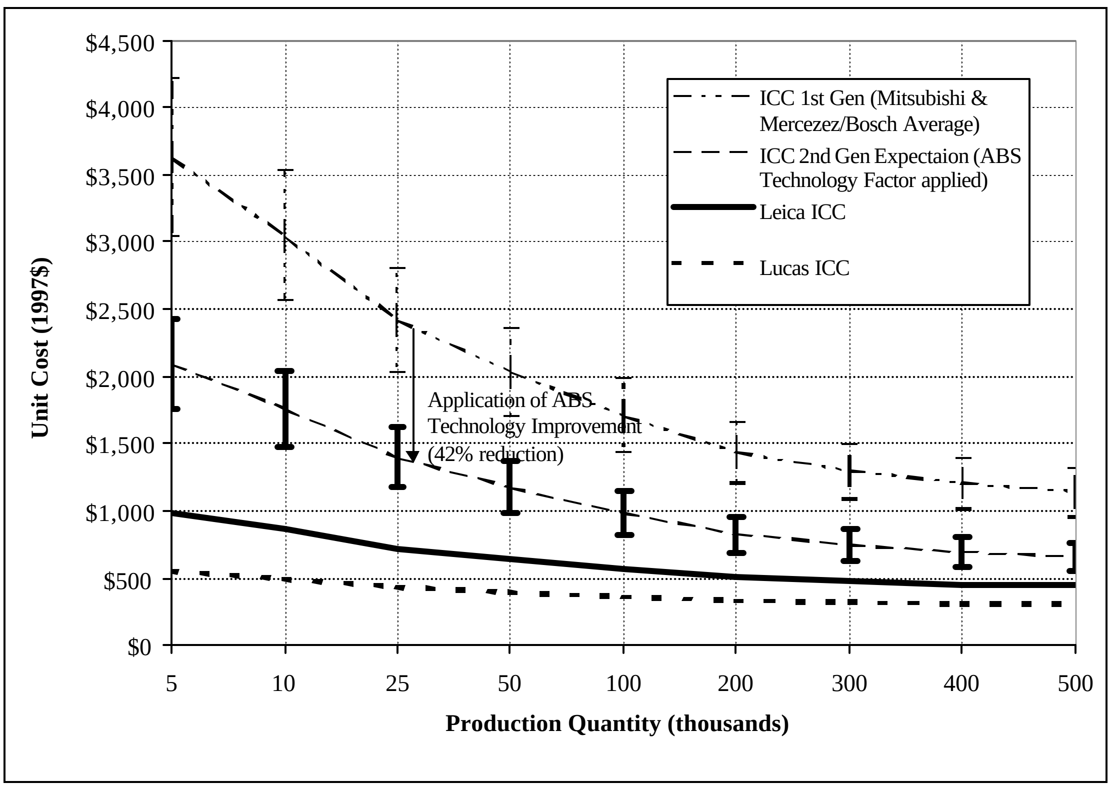

Figure 5-18 Application of Lucas and Leica ICC Systems as Second Generation Systems

With these assumptions, the Lucas and Leica projections are about 45% to 65% of the value of the expected ICC second generation cost estimate. In mass production (500,000 units), second generation ICC systems would be expected to cost about $670, whereas the Leica and Lucas estimates are $440 and $303, respectively.

Thus, even when viewed as second generation systems, the Lucas and Leica ICC estimates are still considerably lower than those expected based for the costs on the Mitsubishi and Mercedes/Bosch first generation estimates. There are several possible reasons for this difference:

1. the Lucas and Leica cost estimates are preliminary, and neither is yet under production,

2. the Leica estimate may be lower for valid technical reasons, as Leica claims that their IR sensor-based system will cost less then 50% of a typical radar-based system,

3. the comparative analysis does not take into account technical and performance differences between ABS and ICC systems, and

4. the comparative analysis was based on an ABS development profile from the 1970's to 1990's, whereas the ICC development timeframe is the 1990's and 2000's — these are substantially different timeframes in terms of manufacturing technology.

Whatever the difference, it should be noted that some skepticism exists in the automotive electronics industry concerning some the ICC cost projections that have been reported to date. According to Keith Barks of TRW:

> *I don't know anybody who has a product they can get into the mass market from a cost point of view. We've always talked about $200 to $300 absolute max for the system, and no one's at that level yet.*
>
> — Martin, 1995

5.3.5.2 Existing or Planned ICC Systems Development and testing of ICC systems for automobile applications has been underway in the U.S., Europe, and Japan since the early 1990's. One system has entered production in Japan, another system is poised to enter the European market within the next year, and two additional systems are poised to enter production in the early 2000's. These systems are described in the following paragraphs.

Table 5-9 provides a summary of the 1995 Mitsubishi "Preview Distance Control" ICC System. This system incorporates a high performance laser radar and video system. It is being produced in low rates for the Mitsubishi Debonaire, a Japanese market luxury car. For this analysis, low rate production of ICC systems were assumed to be 10,000 units per year, with a margin of error of ½x (5,000/year) to 2x (20,000/year). The average cost of this system was reported to be $3100.

Table 5-9 1995 Mitsubishi "Preview Distance Control" ICC System (ITS America, 1996)

• Laser radar sensor on front bumper coupled with a rearview mirror video system
• Advanced computer & software
• Throttle and transmission control only (no braking)
• Collision warning
• Low-rate production ICC for Mitsubishi Debonaire; assume production of 10,000 per year or production run -- assumption margin of error is estimated to be 1/2x (5,000/year) to 2x (20,000/year)
• Cost is approximately $3100 in U.S. Dollars (1997)

Table 5-10 provides a technical and development summary of the anticipated 1998/1999 Mercedes/Bosch ICC System. This system incorporates a high performance radar system. Initial low-rate production is anticipated, with initial application as an option for Mercedes luxury cars. For the purposes of this analysis, low rate production of ICC systems was assumed to be 10,000 units per year, with a margin of error of 1/2x (5,000/year) to 2x (20,000/year). It has been reported that this system would eventually be introduced to the European and U.S. family sedan market. The average cost of this system is anticipated to be $3000 in the first year of introduction.

Table 5-11 provides a summary of the anticipated late 90's to early 2000's Lucas ICC System. This system incorporates a high performance radar. Initial application will be as an option for Mercedes luxury cars, with phased in introduction to the European and U.S. family sedan market. Lucas has a target price estimate of $170 on top of conventional cruise control (CCC = $190) based on production of 100,000 units per year.

Table 5-12 provides a summary of an anticipated Late 90s/Early 2000's Leica ICC system. This system incorporates an IR sensor, and is expect to be lower in cost than radar-based ICC systems. Initial applications are undefined, but it is anticipated that it could be applied to a wide range of cars. Lucas has a target price estimate of $250 on top of conventional cruise control (CCC = $190) for production of 500,000 units per year.

Table 5-10 1998/1999 Mercedes/Bosch ICC System (Martin, 1995; Sedgwick, 1997)

- High Performance radar-based ACC
- Radar sensor behind front license plate
- Advanced microprocessor
- Throttle and transmission control only (no braking)
- Low-rate production ICC initially for Mercedes luxury cars; assume 10,000 produced in first year, then growing to the Europe/U.S. family sedan market – assumption margin of error is estimated to be 1/2x (5,000/year) to 2x (20,000/year)
- Cost: About $3000 in year of introduction

Table 5-11 Late 90's/Early 2000's Lucas ICC System (The Intelligent Highway, 1996)

• High Performance radar-based ACC
• Radar sensor behind front license plate
• Advanced microprocessor
• Throttle and transmission control
• Brake control (European version only)
• Low-rate production ICC for initially for Mercedes automobiles; then growing to the family sedan market in both Europe and the U.S.
• Cost: Lucas has a target price estimate of $170 on top of conventional cruise control (CCC=$190) based on production of 100,000/year

Table 5-12 Late 90's/Early 2000's Leica ICC system (IVHS America and NHTSA, 1992)

• Low Cost IR Sensor ICC System
• Infrared sensor located behind rear-view mirror; utilizes optical distance measurement innovation
• Advanced Microprocessor
• Transmission and throttle Control Only (no braking)
• Applications to many vehicles
• Leica Production/Price Estimate: Around $250 on top of conventional cruise control (CCC=$190) for production of 500,000/year

5.3.6 Comparison with "Willingness to Pay" Results

Figure 5-19 provides a comparison of the results of the ABS-ICC cost analysis with the willingness-to-pay survey results from the ICC FOT. As discussed in Chapter 4 *User Acceptance of the ICC System* chapter, median willingness to pay fell between $275 and $475, dependent on whether or not the response came from current users of CCC systems. Thus, it can be seen from the figure that this willingness-to-pay band is just slightly below the costs of a Leica ICC type system at higher production quantities.

5.3.7 ICC Cost Analysis Summary

At a production level of 500,000 units per year, the cost to the consumer of an ICC unit was estimated to range between $303 and $1200. This cost compares to the median willingness-to-pay band of $275 and $475 for nonusers and users, respectively, or the overall median willingness-to-pay of $300, determined from the participant questionnaires.

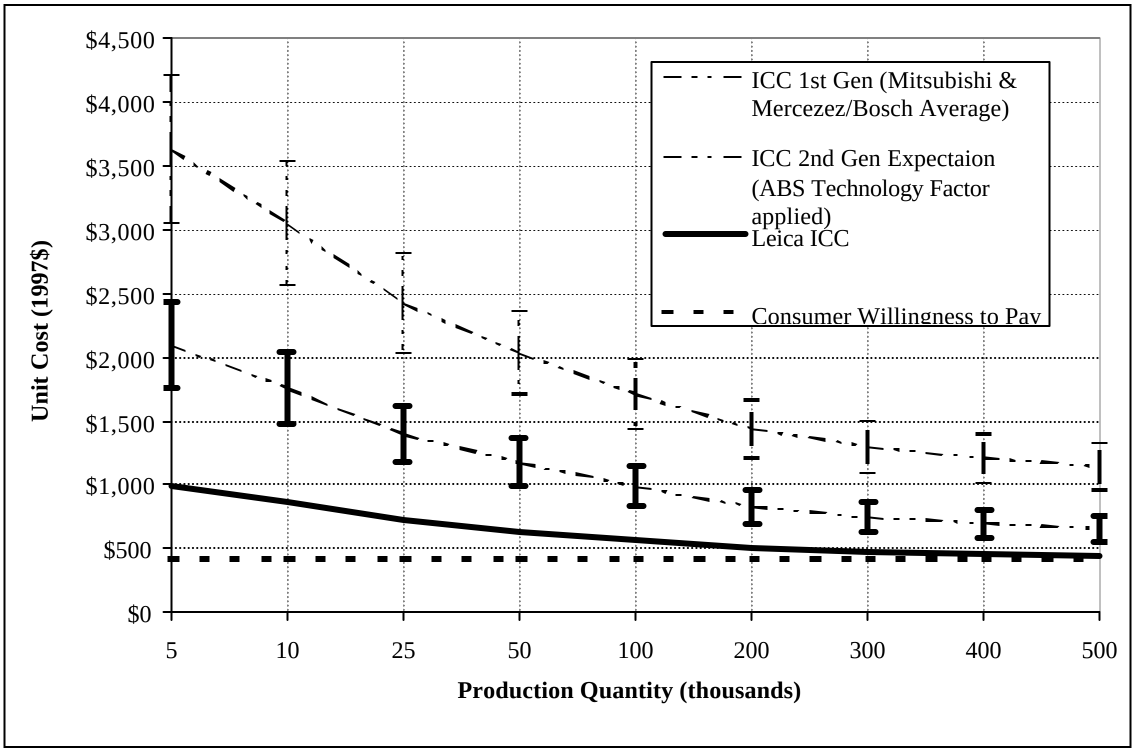

Figure 5-19 Comparison with Willingness to Pay Results

5.4 Institutional Deployment Issues

5.4.1 Objective

The objective of the ICC Institutional Issues study was twofold:

- Describe the institutional issues that were encountered during the operational test that could be projected to affect full deployment
- Identify the solutions to those issues

5.4.2 Approach

During the initial stages of the ICC project, the Institutional Issues Study Team sent questionnaires to thirteen project participants (not volunteer drivers) from the ICC operational test and reviewed project documentation. The Institutional Issues Study Team then conducted personal interviews with the thirteen project participants and other industry representatives. These interviewees represented state government, private industry, and academia. The information collected from the questionnaires and interviews provide the basis for this institutional issues study. The results are summarized next.

5.4.3 Results

As part of the overall evaluation of the Intelligent Cruise Control (ICC) FOT, the Institutional Issues Study addressed non-technical constraints that might hinder the development of the ICC FOT or full deployment of ICC technology. Many of the study findings dealt with the field operational test process and identification of means for improving its effectiveness. These findings, while important to DOT in refining future FOTs, were not considered directly relevant to evaluation of the ICC and were, therefore, documented separately as an internal project memorandum. However, the study did identify three issues directly relevant to future deployment of ICC-like systems that are discussed below: (1) ICC Standards, and (2) Instruction of New ICC Users.

Issue: Standards ICC FOT project participants mentioned the need for standards in ICC technology as an issue. Specifically, they indicated that the Federal Government should be involved in developing standards for these systems and that the lack of standards for ICC technology might adversely affect their development. ICC standards could be both in terms of guidelines for testing new ICC systems as well as for performance and driver interface features of ICC systems. Further, interviewees stated that many unknowns surround ICC systems, so it is in the best interest of manufacturers to work with the Federal Government to develop the ICC system standards.

Issue: Instruction of New ICC Users Several concerns were expressed regarding how drivers would use the ICC system under various circumstances and that this could influence safety. For example drivers might become too dependent on the ICC system resolving critical driving situations, or they might not appreciate the performance limits of the system, especially in inclement weather. The FOT verified that there were rare instances when drivers appeared to be over-reliant on the ICC system to resolve situations. Proposed solutions to these concerns offered by project participants were to gauge how drivers react to the ICC system and develop instructional materials to promote appropriate use of ICC by new users.

5.4.4 Institutional Deployment Issues Summary

The study identified two issues directly relevant to future deployment of ICC-like systems: ICC standards and instruction of new ICC users. Participants indicated that the Government should be involved in developing standards for these systems and that the lack of standards for ICC technology might adversely affect their development. Also, there was some consensus that the development of instructional materials would be useful to help ensure that new users of ICC operate the system appropriately.

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6. Discussion

As set forth in the Introduction, the evaluation goals were to assess the ICC system with respect to:

- Safety Effects
- ICC System and Vehicle Performance
- User Acceptance
- System Deployment Issues.

In the sections that follow the evaluation findings in each of these areas are discussed in turn.

6.1 Safety Effects

Table 6-1 highlights the major findings with respect to safety. The findings are expressed relative to the Safety Analysis Organization presented as Figure 3-1. The first column of the table identifies the safety category, the second column identifies the performance measure, and the remaining columns describe the major findings and safety implications for ICC versus manual driving and versus driving with CCC. Since a basic finding from the usage data was that ICC was used mostly on freeways and next often on arterials, the results and findings are separated accordingly. There were not sufficient data with ICC to warrant any analysis on the other road types.

6.1.1 Usage

Most use of ICC was on freeways. On freeways, when ICC was available it was used 58 percent of the time. ICC usage was considerably less on arterials, only six percent of the time it was available. When ICC was available on arterials, young drivers used it less than 5 percent of the time and older drivers used it 10 percent of the time. On freeways ICC was used considerably more of the time than CCC. Thus for freeways, ICC appears to achieved its goal of making cruise control more convenient to use. If there are safety benefits attendant to the use of ICC they are most likely to appear on freeways. Furthermore, older drivers are likely to benefit more than younger drivers are, because older drivers use cruise control more than younger drivers. Among 5-week participants, ICC usage remained fairly stable across the four weeks that ICC was available. This finding may suggest that the usage levels observed in the FOT may be indicative of long-term usage patterns that can be expected when ICC systems are deployed.

6.1.2 Driving States

The safety analysis in this report is placed in the context of a *safety analysis framework*. This *safety analysis framework* is defined in terms of driving states and transitions. The driving states and transitions encompass all driving situations. The main driving states are *closing*, *following separating* and *cruising*. *Cruising* in this study is defined as the absence of any preceding vehicle within 2.4 seconds of the host vehicle. The *closing* state assumes a minimum closing rate of 1.5 m/s. The extent to which drivers can avoid or minimize time in the closing state is considered safety beneficial.

Table 6-1 Summary of Major Safety Findings - ICC Versus Manual and Versus CCC – Freeways and Arterials

Safety Category	Performance Measure	Major Safety Finding <u>Freeways</u>			Safety Implication <u>Freeways</u>		Major Safety Finding <u>Arterials</u>			Safety Implication <u>Arterials</u>	
		Man	**CCC**	**ICC**	**ICC Vs Man**	**ICC Vs CCC**	**Man**	**CCC**	**ICC**	**ICC Vs Man**	**ICC Vs CCC**
Usage	Percent of Time Used When Available	-	38	58	pos.	pos.	-	4	6	pos.	pos.
	Percent of Distance Driven When Available	-	41	62	pos.	pos.	-	12	15	pos.	pos.
States	Percent of Time in Closing State	6.8	5.2	5.1	pos.	neu.	4.4	6.5	8.5	neu.	neu.
	Percent of Time in Closing Close Sub-State	0.8	0.4	0.2	pos.	pos.	0.2	0.1	0.2	neu.	neu.
Transitions	Lane Change Rate (per hundred kilometers)	19.0	7.0	8.0	pos.	neu.	17.0	10.0	9.0	pos.	neu.
	Lane change Rate From Closing State (per hundred kilometers)	3.46	1.57	1.04	pos.	pos.	3.09	0.81	0.62	pos.	pos.
	Cut-In Rate (per hundred kilometers)	20.0	12.0	12.0	pos.	neu.	7.0	1.0	3.0	pos.	neu.
	Cut-In Rate To Closing State (per hundred kilometers)	4.42	2.10	2.48	pos.	neu.	1.51	0.29	0.64	neu.	neu.
Basic Safety Performance Measures	Time-Headway (seconds)	1.7	2.2	1.9	pos.	neg..	2.3	3.0	2.7	pos.	neg.
	Velocity (km/h) Velocity Variability (km/h)	96 11.1	110 2.8	106 4.4	neu. pos.	neu. neg.	62 -	77 -	77 -	neu. -	neu. -
	Acceleration Levels	wide band	narrow band	in between	pos.	pos.	wide band	narrow band	in between	pos.	pos.
	Acceleration Variability	high at low speed	smallest	low	pos.	pos.	high	smallest	low	pos.	pos.
	Braking Frequency (per hundred kilometers)	24.5	12.0	5.0	pos.	pos.	90.0	41.0	32.0	pos.	pos.
	Braking Force > 0.15 g (per hundred kilometers) Braking Force > 0.20 g (per hundred kilometers)	3.30 1.39	0.01 0/rare	0.10 0.04	pos. pos.	neu. neu.	32.0 17.0	3.0 5.8	9.0 14.9	pos. pos.	neg. neg.
	Response Time (seconds)	1.7	2.3	2.0	neg.	neu.	1.9	1.95	2.3	neg.	neg.

Safety Category	Performance Measure	Major Safety Finding Freeways			Safety Implication Freeways		Major Safety Finding Arterials			Safety Implication Arterials	
		Man	**CCC**	**ICC**	**ICC Vs Man**	**ICC Vs CCC**	**Man**	**CCC**	**ICC**	**ICC Vs Man**	**ICC Vs CCC**
	Closing Rates (m/s)	-1.4	-1.7	-1.3	neu.	pos.	-1.8	-2.5	-2.0	neu.	pos.
	Time-Headway (seconds)	1.5	1.6	1.7	pos.	pos.					
Safety-Critical Performance Measures	Velocity (km/h)	88	100	99	neg.	neu.					
	Braking Frequency	high	low	low	pos.	neu.					
	Braking Force	low proportion	middle proportion	high proportion	neg.	neu.					
	Response Time to Critical Events	-	-	slightly higher	neg.						
	State Space Boundary Crossing Rate (crossing of B3 per hundred kilometers)	14.0	6.0	4.0	pos.	pos.					
	State Space Boundary Crossing Time (% of time below B3)	0.17	0.08	0.03	pos.	pos.					
	Close Calls (per hundred kilometers)	6.2	3.8	3.4	pos.	neu.	2.2	5.2	5.6	neg.	neu.
	Most Severe Close Calls (per hundred kilometers)	0.5	0.1	0.2	pos.	neu.	0.9	1.6	2.2	neg.	neg.
	Pre-Crash Scenario Rate	high	low	low	pos.	neu.					
	Critical Pre-Crash Scenario Rate	low	high	middle	neg.	pos.					
	Critical Pre-Crash Scenario Parameters	Insufficient data			neu.	neu.					
Driver Perceptions of Safety	Survey Ratings	Manual most safe Felt safe using ICC More cautious driving with ICC			pos.	neu.					
Widespread Safety Effects	Predicted Collisions (percent reduction compared to manual)	-	2	17	pos.	pos.					

pos. – positive neu. –.neutral neg. – negative

Overall drivers spent 498 hours in one of the driving states on freeways above 40 km/h, and 387 hours on arterials above 40 km/h. On freeways, ICC spent less time in the *closing* state compared to manual driving and about the same time compared to CCC. ICC spent less time in the more critical sub-state, *closing-close*, compared to both manual driving and CCC. ICC also spent substantially less time (1.7 percent) in another safety critical sub-state, following-close, compared to both manual (12.8 percent) and CCC (2.5 percent). Finally, ICC spent proportionately more time than manual and CCC in the more safety benign sub-state of *following-far*. These results suggest that, in terms of the amount of time in safety-critical driving states on freeways ICC has a safety benefit.

On arterials, the ICC system spent proportionately more time in the *closing* (8.5 percent) and *following* (39.5 percent) states, and less time in the *cruising* state (48.3 percent) than either manual or CCC. Virtually no ICC closing events were in the most safety critical sub-state of *closing-close-rapidly*. More time in the closing states is a safety concern for the ICC system on arterials. However, with the sparsity of data on arterials, these results should be treated as unreliable.

6.1.3 Transitions

The two main types of transitions examined in this study are lane change and cut-in. As lane changes and cut-ins increase turbulence in traffic flow, an ICC contribution to a reduction in either would be likely to make a contribution to safety as well.

6.1.3.1 Lane Changes On freeways there were significantly fewer lane changes with ICC and CCC when compared to the number of lane changes made in the manual mode. The number of lane changes per hundred kilometers was reduced from approximately 19 for manual to 8 for ICC and 7 for CCC. Furthermore, the number of lane changes per hundred kilometers <u>from</u> the closing state was substantially lower for ICC (1.04) compared to both manual (3.46) and CCC (1.57). If lane changes increase the probability of crashes, then ICC reduces the probability of crashes attributable to lane changes and thus provides a safety benefit. The number and pattern of lane changes indicate a strong safety benefit for ICC compared to both manual and CCC.

On arterials, the number of lane changes per hundred kilometers was reduced from approximately 17 for manual to 9 for ICC and 10 for CCC. The number of lane changes per hundred kilometers <u>from</u> the closing state was substantially lower for ICC (0.62) compared to both manual (3.09) and CCC (0.81). The number of lane changes on arterials indicate a strong safety benefit for ICC compared to both manual and CCC.

6.1.3.2 Cut-Ins On freeways there were significantly fewer cut-ins with ICC and CCC when compared to the number of cut-ins made in the manual mode. The number of cut-ins per hundred kilometers was reduced from approximately 20 for manual to 12 for both ICC and CCC. The number of cut-ins per hundred kilometers <u>to</u> the closing state was lower for ICC (2.48) compared to manual (4.42) and about the same for CCC (2.10). The number and pattern of cut-ins indicate a strong safety benefit for ICC compared to both manual and CCC. Cut-ins did not increase with ICC headway setting.

On arterials there were significantly fewer cut-ins with ICC when compared to the number of cut-ins made in the manual mode. The number of cut-ins per hundred kilometers was reduced from approximately 7 for manual to 3 for ICC. The number of cut-ins on arterials thus indicates a strong safety benefit for ICC compared to manual. There were insufficient data to draw any conclusions from the CCC results.

6.1.4 Basic Safety Performance Measures

6.1.4.1 Time-Headway When using ICC, drivers maintained longer average time-headway than they did when they drove manually. Only with the 1.0 s time-headway, did average time-headway approximate that observed under manual driving. Regardless of cruise control mode, older drivers maintained longer average time-headway than did younger drivers. Thus if longer time-headway is assumed to be safer, then ICC use will result in a safety benefit.

6.1.4.2 Velocity When using ICC on freeways, drivers maintained higher velocities than they did when driving manually. These velocity differences were interpreted to be the result of the different traffic conditions under which drivers choose to drive manually or with cruise control. The increase in ICC usage relative to CCC was at velocities below 105 km/h. Thus, it appears that ICC enabled comfortable cruise control usage in more dense traffic than that in which drivers felt comfortable using CCC. The most common velocity was the same for manual, CCC, and ICC driving, which suggests that in all three cruise modes drivers had the same speed objective, and that lower velocities were indicative of traffic congestion.

Less variability in velocity is assumed to be safer, because it should result in a reduction in the velocity differences between vehicles, and thus fewer catalysts for rear-end collision situations. Variability in velocity was evaluated by examining the standard deviation in velocity. The standard deviation in velocity was much lower for ICC than for manual driving, and slightly higher for ICC than for CCC. The difference between CCC and ICC was most likely the result of the ICC system adjusting velocity to accommodate slower moving preceding vehicles, something CCC cannot do without driver intervention. However, just as drivers disengage CCC when traffic makes cruise control less convenient than manual control, they also turn off ICC when traffic exceeds that system’s capacity to conveniently adjust headway. As a result, much of the difference in velocity variability between ICC and manual may be the result of manual driving occurring in heavier traffic than ICC driving. Indeed, the level of service model used in the evaluation indicated that manual driving involved substantially more travel under congested conditions. Nonetheless, the design of the ICC system should reduce velocity variability relative to manual control, because the system measures range with greater accuracy than a human can, and because the system makes small variations in throttle setting at a higher sampling rate than would be expected from human controllers.

6.1.4.3 Acceleration Accelerations, particularly high negative accelerations, imply reduced safety. High acceleration variability is associated with greater velocity variance between vehicles, and differences in velocity are associated with increased crash rates. CCC accelerations had a narrow band of variation and ICC accelerations had a somewhat wider band of variation. Manual driving showed the widest range of variation. For all cruise modes accelerations on arterials had a slightly wider band than accelerations freeways. There is a trend for acceleration variability to decrease with velocity. Overall, the tendency for ICC to reduce acceleration variation compared to manual driving suggest a possible safety benefit.

6.1.4.4 Braking Frequency Because the ICC system automatically slows the vehicle, through throttle adjustment, when slower vehicles are encountered, the need for drivers to intervene with the brake to slow the vehicle should be reduced. This was intended to provide a convenience to the ICC user. Compared to CCC, ICC reduced the frequency of braking on freeways by 58 percent, despite the finding that ICC was used in heavier traffic than CCC. Braking in ICC mode was 80 percent less than braking frequency per kilometer in manual mode. Thus ICC demonstrably reduced braking frequency, which provided a clear convenience factor, probably reduced driver fatigue, and may have also reduced exposure to rear-end crashes.

6.1.4.5 Braking Force On dry pavement, maximum deceleration may approximate –0.7 g, and –0.3 to –0.5 g on wet pavement. Braking force above –0.3 g was rare in the FOT, and the braking force differences between manual, CCC and ICC, that are the subject here, were decelerations in the range between –0.05 and –0.3. The overall distribution of braking frequency versus severity is vastly less for ICC than manual (generally by more than one order of magnitude) and is more comparable to CCC. For example, the relative frequency of 0.1 g brakings on freeways per hundred kilometers traveled (at speeds greater than 80.5 km/h and with lead vehicle present) is about 0.11 for ICC compared to 0.14 for CCC and 5.00 for manual. The relative frequency of 0.2g brakings on freeways per hundred kilometers traveled is about 0.23 for ICC compared to 0.0 for CCC and 0.88 for manual.

The number of brake press of all intensities per kilometer was far greater in manual mode. However, if the proportion of brake presses within a mode is considered, then that proportion is higher for ICC brake presses in the range between –0.1 and –0.3 g. Thus ICC markedly reduced the overall number of brake presses, and decreased the absolute number of brake presses of all intensities. However, given that a brake press was required, ICC increased the probability that relatively intense braking would occur.

As intense braking implies large velocity differences between the ICC vehicle and following or preceding vehicles, the increase in the probability that braking will be intense has to be considered a safety concern. This small increase in risk (the overall number of instances was small) should be weighed against the benefits, especially the benefits of decreased braking frequency.

6.1.4.6 Response Time The time between the onset of a preceding vehicles brake lights and the pressing of the ICC vehicle brake pedal was recorded, primarily to assess whether there was evidence that ICC would lull drivers into a non-responsive state. A small number of videos were identified in which it appeared appropriate to assess the brake-light stimulus to brake-pedal press latency. On freeways, ICC latencies were about a 0.3 second longer than manual latencies, but shorter than CCC latencies. On arterials ICC latencies were longer than both manual and CCC latencies, but the difference was less than a half-second, and not statistically reliable. Furthermore, correlational analyses indicated that for all modes there was a positive correlation between time-headway and response time. Thus the longer response times observed with ICC may have been the result of longer ICC headway rather than driver non-responsiveness. It was also pointed out that in order for the ICC system to function as intended, the driver had to resist pressing the brake pedal. Thus, to some extent, the system design calls for delayed driver responses. There was no evidence that ICC users delayed responses long enough to pose a demonstrable safety hazard.

6.1.5 Safety-Critical Performance Measures

6.1.5.1 Closing Rate There is some evidence on freeways and arterials that ICC reduces the level of closing rates compared to CCC. In manual driving, drivers had the ability to reduce the closing rates when approaching another vehicle more than CCC, thus achieving a smoother interaction with the preceding vehicle. ICC tended to match this ability more than CCC.

Closing rates were inversely proportional to ICC headway setting on freeways, whereas on arterials, closing rates were proportional to ICC headway setting. Overall, ICC may be considered safety neutral compared to manual driving in terms of average closing rates on freeways and arterials.

6.1.5.2 Time-Headway During Closings During closings, ICC overall had the longest time-headways and manual had the shortest time-headways. The ICC time-headways for each setting were longer than the headways for manual. The time-headways for manual and ICC with a setting of 1.0 second were not substantially different. The longer time-headways suggest a safety benefit.

6.1.5.3 Velocity During Closings During closings, the velocities for ICC overall and CCC were about the same and greater than that for manual. The ICC velocities for each headway setting during closings were all greater than that for manual. This suggests a safety dis-benefit for both ICC, including each of the headway settings, and CCC. The ICC velocities during closings were inversely proportional to the ICC headway setting, although the differences in velocities were not substantial. From a velocity perspective, this headway-setting effect appears to be neutral with respect to safety.

6.1.5.4 Braking During Closings The proportion of brake presses for ICC at deceleration levels greater than or equal to -0.2 g. was greater than that for manual and CCC, and was also about double the amount when the states were not restricted to the closing situations. This is a safety concern for ICC as it indicates that during closings braking with ICC was more apt to be harder than braking with CCC or manual.

6.1.5.5 Response Time to Critical Events Driver time responses for critical events, whether based on short time headways, large levels of lead vehicle deceleration, or large levels of host vehicle velocity reduction, appear to be slightly larger for ICC compared to manual driving. In most cases the differences were not statistically significant. There were not sufficient data for comparison with CCC. The response time measure is therefore viewed as a safety concern, but not an indication of a general safety problem with the ICC system.

6.1.5.6 State Space Boundary Crossings State space boundaries were defined in a range range-rate space that may be thought of as safety surrogates. That is, below these boundaries the ICC vehicle is close and closing rapidly with a preceding vehicle, and this is regarded as less safe than being farther away and, or, closing less rapidly. ICC markedly reduced the rate per kilometer at which drivers exceeded the boundaries, both relative to manual driving and relative to using conventional cruise control. The proportion of time spent within the boundaries was also reduced by use of the ICC system, but this benefit was only evident when compared to manual driving.

Because it helps drivers maintain longer headways, and because it automatically decelerates the vehicle in response to lead vehicle decelerations, the ICC system reduces the frequency and duration of occasions when the equipped vehicle is close and/or closing rapidly on a preceding vehicle.

6.1.5.7 Close Calls

Close Call Frequency. On freeways, the ICC system appears to have markedly reduced the number of close calls that would otherwise have been observed. Although the difference was not statistically reliable, the number of close calls per kilometer was less for ICC than for CCC, suggesting that the difference between manual and ICC cannot be attributed solely to differences in traffic density. As might be expected, younger drivers had more close calls than middle-aged or older drivers, but the cruise control effect was the same for all groups – ICC was associated with fewer close calls regardless of age.

On arterials the results were mixed. Overall, both CCC and ICC had more close calls per kilometer than manual driving. However, closer inspection of the data showed that most drivers experienced the same or fewer close calls with ICC than in manual. There was a subset of 22 drivers who experienced many more close calls with either cruise control mode (ICC or CCC) than they did driving manually. Thus, there appears to be a sub-population of drivers that use cruise control recklessly. For these drivers, who constituted about a third of the sample, ICC increases close call risk because it increases the likelihood that cruise control will be used. Though beyond the scope of this report, it is plausible that simple educational measures could address the problem these drivers pose.

Because ICC is used primarily on freeways, the ICC benefit in decreasing close calls on freeways probably exceeds the increased risk associated with limited arterial use by a few drivers.

Close Call Severity. On freeways the *most severe* close calls, those for which an actual crash would have resulted in severe injuries or death, were less frequent when ICC was used than when manual control was exercised.

On arterials, the same trend was observed as for close calls overall – a subset of very risky drivers had a very high rate of *most severe* close calls when using ICC or CCC, and this raised the average frequency of *most severe* close calls above that for manual driving. However, if the proportion of drivers within a mode who have *most severe* close calls is examined, then ICC and CCC look better than manual driving. That is, 66 percent of the sample had a rate of *most severe* close calls that exceeded 1000 close calls per million vehicle kilometers. Yet for CCC and ICC the percentages of drivers with rates above 1000 per million vehicle kilometers were 19 percent and 29 percent respectively. Thus more than two-thirds of the sample had fewer *most severe* close calls with ICC, and one-third saw the number of *most severe* close calls increased markedly with ICC, so markedly that their rates mask the wider benefit.

ICC reduces the severity of close calls on freeways. ICC appears to be more hazardous on arterials, when used by (a minority of) drivers who do not appear to use the system in an appropriate manner.

6.1.5.8 Pre-Crash Scenario Rate Four common pre-crash scenarios that are counted in national databases, were identified in the data stream recorded in the vehicles. In the databases these scenarios described the situations just before police reported collisions occurred. In the ICC data stream, these scenarios are situations that fit the pre-crash scenario descriptions except that in the ICC case, no collisions occurred. It is hypothesized that the rate of occurrence of pre-crash scenarios may be related to the rate of occurrence of rear-end collisions. The results from the field operational test indicated that on freeways, ICC use was associated with a decrease in the occurrence of each of the four types of pre-crash scenarios examined. This therefore indicates a safety benefit derived from ICC use.

6.1.5.9 Critical Pre-Crash Scenarios An analysis was conducted of 192 videos (96 drivers). For each driver the highest observed braking intensity among videos triggered by braking was examined and the hypothetical highest required braking intensity for videos triggered by "close encounters" was examined. These analyses showed that for the subset of cases defined as critical pre-crash scenarios, ICC driving included 20 out of a total of 41 cases. The highest braking level for ICC driving was 0.30 g and involved the ICC vehicle braking for a lead vehicle that was decelerating. Each of the most severe braking events was examined in detail using the video data. As noted above under response times, the video analysis seemed to confirm the observation with the limited data available that ICC drivers appeared to wait on the ICC system to respond to an evolving situation to avoid disengagement and then intervened late, braking at a high level, to successfully resolve the situation. The video analysis concluded that, while the ICC driver may have contributed to the severity of situations by waiting on the system and was a cause for some concern, all the situations were resolved by the driver and none of the situations indicated a general safety problem for the ICC system. It was also noted that the ICC situations may have involved a learning component; i.e., the ICC drivers were learning how best to use the system and that the critical situations noted might decline with more experience. There was some evidence to this effect since none of the more severe "waiting" cases occurred beyond the first week of experience with ICC. However more research is needed to confirm this.

6.1.6 Driver Perceptions of Safety

Users ranked manual driving as safer than ICC driving, yet agreed that ICC systems would increase safety. The users also indicated that they felt safe using ICC.

The pattern of answers on the questionnaire suggests that some users did not understand the questions, or that they were inclined to provide responses that pleased the questioners. There was no indication from users that they felt the system was unsafe. The pattern of responses indicates that users felt the system was safe.

6.1.7 Widespread Safety Effects

Monte Carlo computer simulations that used ICC FOT data as inputs suggested that if all vehicles were equipped with the ICC system, there would be a 17 percent reduction in rear-end collisions on freeways for two specific types of collisions: (1) ICC vehicle approaching a slower vehicle traveling at a constant velocity, and (2) a lead vehicle decelerates in front of an ICC vehicle. Although not estimated under this current effort, additional safety benefits from ICC use would be expected from a reduction of other rear-end collisions involving cut-ins and lane changes, and from use of ICC on roadways other than freeways.

6.2 ICC System and Vehicle Performance

In Chapter 2 the basic ICC system performance was characterized. Based on a series of pilot tests that were conducted prior to and during the FOT, the system worked reliably under a wide variety of conditions. It was more aggressive in extending gaps to the desired time-headway than in closing gaps, which resulted in longer than nominal mean time-headway under most conditions.

The IR system's ability to distinguish small near targets from distant large targets was appropriately calibrated for near and far fields such that it was not prone to missing smaller vehicles. However, blind spots within its lane coverage were identified which could cause the system to momentarily lose motorcycles traveling to the right or left of a lane, or other vehicles that are only partially within the same lane as the ICC vehicle. The blind spots were not viewed as particularly problematic from a safety perspective. Furthermore, repositioning of the sensors to more outboard locations on the host vehicle could eliminate the blind spots.

During the FOT a number of reliability-related observations were made. There were instances of false positives that correlated with overhead abutments, guardrails, and the passing of tractor trailers in adjacent lanes. There were instances of dropped targets over hills, in dips and around curves. Further, the system was observed to not perform well in snow and heavy rain. It is also interesting to note that instances of stopped vehicles on freeways were observed during the FOT. None of these stoppages seemed to pose any particular hazard since they occurred either during periods of congestion at lower speeds or at large distances and were preceded by brake light warnings from other vehicles. These observations by the evaluation team seemed to be consistent with participants' responses on the questionnaires and during focus group sessions (Fancher, 1998) in the sense that whereas overall performance of the system was adequate, the drivers did recall during their critique of the system occasional problems. On the positive side, the system was observed to track motorcycles properly, and the sweep sensor did track vehicles in curves. While a formal quantitative reliability study was not conducted, the video data together with the sensor data do provide a basis for such an examination. As a matter of fact, a preliminary assessment of reliability based on a limited set of these data was performed. In the Recommendation section, this idea of a reliability study based on comparing video data and sensor data from the FOT is further elaborated upon.

6.3 User Acceptance of the ICC System

The FOT participants expressed a strong level of acceptance of the ICC. Both prior users of CCC and non-users of CCC preferred the ICC to CCC. Participants who said they were already cruise control users ranked ICC as their most preferred mode. Those who said they didn't use cruise control were less clear in their mode preference. The relative preferences of both groups mirror the ICC usage patterns, as summarized in section 6.1.1 above.

Participants overwhelmingly ranked ICC over CCC and manual for convenience, comfort, and enjoyment. However, non-users were equivocal in their preference for ICC over manual for "personal use". This inconsistency implies, perhaps, an overreaching compliance with the questionnaire expectations.

Participants, particularly those who had the ICC system for only one week, indicated that they would be more comfortable with the system given more time. This may indicate that the ICC system introduces a new dimension to driving that may require a learning process of more than a week before drivers feel fully comfortable with it. To the extent that there is a learning process, consideration of extended orientation and training of new users may be appropriate.

Participants said that they were most likely to use ICC on freeways. A significant number indicated they would also use it on rural and other two-lane roads. Some were also comfortable using ICC on hilly and winding roads. These suggest that future ICC systems should be designed with their use on secondary roads, of varying grades and curvatures, in mind.

Although those few drivers who experienced the ICC in rain and snow felt comfortable using the ICC, their level of comfort belied weather-related operational problems with the sensor that were acknowledged prior to the FOT. In certain conditions snow buildup would prevent detection of a forward vehicle. Proceeding at a given set speed, the driver might be lulled into a false sense of security, should the vehicle slow down. Due to limited exposure, close calls of this nature did not occur in the FOT. Nevertheless, that drivers had somewhat greater levels of comfort with CCC in rain and snow may indicate the participants' awareness of the ICC sensor's bad-weather problem.

The last user-preference question addressed acceptability of having ICC succeed CCC as the standard cruise control device. There was a high expressed level of comfort in seeing ICC replace CCC in the future, particularly amongst the 40-50 year-old participants.

In addition to preference, participants were queried on their disposition to pay for ICC. Drivers' median willingness-to-pay was about $300 for a ICC system when buying a new car. Prior cruise control users reportedly would pay more than $475, and non-users $275, a difference more or less consistent to their expressed relative comfort with ICC.

Drivers of each age group expressed more than neutral willingness to pay for ICC, with users significantly more willing. Middle-aged users, however, expressed uniformly high willingness-to-purchase, consistent with their high level of acceptance for ICC.

6.4 System Deployment Issues

6.4.1 ICC Effects on Traffic Flows

Under certain conditions of short time-headway settings (e.g., 1.0 second) and high speeds, ICC systems could improve roadway capacity. Longer time-headway settings (e.g., 2.0 seconds) could reduce roadway capacity. Alternative, non-linear time-headway control algorithms could improve roadway capacity beyond that of the tested system. Also, alternative algorithms could reduce the impact on traffic flows of instabilities caused by multiple ICC equipped vehicles tracking one another.

6.4.2 ICC Effects on Fuel Consumption and Emissions

Use of the ICC system reduces throttle fluctuations and, thus, the frequency and levels of acceleration. These factors will result in reduced fuel consumption and emissions for ICC driving.

6.4.3 Projected ICC Costs

At a production level of 500,000 units per year, the cost to the consumer of an ICC unit was estimated to range between $303 and $1200. This cost compares to the median willingness-to-pay band of $275 and $475 for nonusers and users, respectively, or the overall median willingness-to-pay of $300, determined from the participant questionnaires.

6.4.4 Institutional Issues

The study identified two issues directly relevant to future deployment of ICC-like systems: ICC standards and instruction of new ICC users. Participants indicated that the Government should be involved in developing standards for these systems and that the lack of standards for ICC technology might adversely affect their development. Also, there was some consensus that the development of instructional materials would be useful to help ensure that new users of ICC operate the system appropriately.

7. Conclusions

The following is a summary of the significant conclusions of the ICC evaluation organized into the four evaluation goal areas.

7.1 Safety Evaluation Goal #1 – Evaluate Safety Effects of the ICC System

The following is a discussion of the safety surrogate measures, driver perceptions, and modeling of ICC safety benefits that supported the overall safety conclusions. As a convenience to the reader, the various indicators used for evaluating ICC safety are summarized in Table 7-1 below. The indicators apply to both freeway and arterial roadways except where noted. The table also shows how these indicators were interpreted in terms of whether they indicated a safety benefit, a safety neutrality, or a safety concern for the ICC system.

The challenge to the evaluators of the ICC system was to integrate the various indicators listed in Table 7-1 into an overall conclusion regarding the safety effect of ICC use. In doing this, several important observations were made:

1. An examination of the potential safety benefits yielded the following considerations:

- there were many more indicators of potential benefits than of safety concerns,
- these benefits accrued over most conditions that ICC drivers were exposed to, and
- the generally positive indications of these measures were further supported by the subjective responses of the FOT participants and the analytical modeling results of widespread ICC use.

2. An examination of the safety concerns, including detailed video examination of many individual driving situations, yielded the following ameliorating considerations:

- the driving situations causing concern were rare events which most ICC drivers had very limited exposure to,
- the occurrence of events causing concern may decline as ICC drivers gain more experience with the system,
- the individual safety-critical cases examined were all successfully resolved by the ICC drivers, and, therefore,
- given the above, it was concluded that these concerns did not represent a general safety problem or indicate any inherent safety deficiency with the ICC system.

Based on the above observations, the overall conclusion of the evaluators was that use of the ICC will result in net safety benefits if widely deployed.

Table 7-1 Summary of Significant Safety Findings

Safety Surrogate Measure	*Indicates Safety Benefit*	*Safety Neutral*	*Indicates Safety Concern*
1. Usage	+		
2. Driving States and Transitions			
2.1 Time in Closing States (Freeways)	+		
2.2 Time in Closing States (Arterials)		0	
2.3 Time in Closing Close Sub-states (Freeways)	+		
2.4 Time in Closing Close Sub-states (Arterials)		0	
2.5 Lane Changes	+		
2.6 Cut-ins	+		
3. Overall Driving Behavior			
3.1 Time-Headway	+		
3.2 Velocity		0	
3.3 Velocity Variability (Freeways)	+		
3.4 Acceleration	+		
3.5 Acceleration Variability	+		
3.6 Braking Frequency	+		
3.7 Braking Force	+		
3.8 Response Time			-
4. Behavior in Safety-Critical Situations			
4.1 Closing Rate		0	
4.2 Time Headway (Freeways)	+		
4.3 Velocity (Freeways)			-
4.4 Braking Frequency (Freeways)	+		
4.5 Braking Force (Freeways)			-
4.6 Response Time (Freeways)			-
4.7 State Space Boundary Crossings (Freeways)	+		
4.8 Close Calls (Freeways)	+		
4.9 Close Calls (Arterials)			-
4.10 Most Severe Close Calls (Freeways)	+		
4.11 Most Severe Close Calls (Arterials)			-
4.12 Pre-crash Scenarios (Freeways)	+		
4.13 Critical Pre-crash Scenarios (Freeways)			-
5. Driver Perceptions of Safety	+		
6. Estimate of Widespread Safety Benefits	+		

7.1.1 Usage of the ICC System

ICC drivers in the FOT, on average, used the ICC system for 19 hours and drove about 1646 kilometers. The ICC system was used extensively on freeways, approaching 60 percent usage on trips greater than 15 minutes. This usage was about 50 percent greater than that of conventional cruise control (CCC). The ICC system was used about 6 percent of the time on arterials, about 50 percent more than CCC. The ICC system was used in greater levels of traffic congestion than CCC; e.g., 26.5 percent more than CCC in moderate levels of traffic congestion.

From a safety perspective, the usage patterns of ICC drivers would tend to promote safer driving. More specifically, ICC drivers tended to use ICC predominately on freeways under conditions of light or moderate traffic. These conditions are generally more safety benign involving fewer interactions with other vehicles and vehicles traveling at relatively uniform velocities, albeit higher velocities.

7.1.2 Driving States and Transitions

7.1.2.1 Indicators of a Safety Benefit for ICC:

Time in Closing States (Freeways) – Driving with the ICC system resulted in less proportion of time spent closing on a lead vehicle; 5.1 percent of the time for ICC versus 6.8 percent for manual and 5.2 percent for CCC.

Time in Closing Close Sub-state (Freeways) – On freeways, driving with the ICC system resulted in the least time spent in states of closing at headways under 0.8 seconds (close) compared to manual or CCC driving.

Lane Changes - The number of lane changes on freeways and arterials when using ICC is less than manual driving. For example, on freeways, the rate of lane changes for ICC driving was about 8 per 100 km in contrast to about 19 for manual. (CCC was about 7). Lane changes for ICC were less likely to result in a closing state; 1.04 lane changes per 100 km of ICC driving resulted in a closing state as compared to 3.46 for manual driving and 1.57 for CCC driving. ICC lane changing also resulted in proportionately fewer instances of ending in states of closing, following, or separating at headways under 0.8 seconds (close) compared to manual driving (14 percent for ICC versus 21 percent for manual). Most importantly, ICC driving resulted in significantly fewer instances of lane changing from closing-close situations (2 percent of lane changes for ICC versus 8 percent for manual and 7 percent for CCC). This is seen as evidence that ICC driving reduces the need for drivers to make safety-critical lane changes in response to slower traffic.

Cut-ins - The frequency of cut-ins on freeways and arterials when using ICC is less than manual driving and equal to CCC driving. For example, on freeways, the rate of cut-ins for ICC driving was about 12 per 100 km in contrast to about 20 for manual. Furthermore, the rate of cut-ins that resulted in a closing state is also less for ICC (about 2.48 per 100 km) than for manual (about 4.42 per 100 km) and about the same for CCC (about 2.10 per 100 km). It was also found that increases in ICC headway setting, from 1.0 seconds to 2.0 seconds, did not increase the rate of cut-ins as was hypothesized before the test.

7.1.2.2 Indicators that are Safety Neutral for ICC

Time in Closing States (Arterials) – Driving with the ICC system resulted in a greater proportion of time spent closing on a lead vehicle; 8.5 percent of the time for ICC versus 4.4 percent for manual and 6.5 percent for CCC. Although this could represent a safety concern, it is considered safety neutral because of several important considerations; namely, very little time exposure is involved (only about 0.5 percent of ICC driving is in the closing state on arterials) and there is evidence that the paucity of data on arterials produced unreliable results (an alternative analysis that aggregated the data over all ICC drivers produced opposite results; i.e., ICC had the least time in closing states).

Time in Closing Close Sub-state (Arterials) – On arterials, driving with the ICC system resulted in about the same percent of time spent in states of closing at headways under 0.8 seconds (close) as manual and CCC driving.

7.1.3 Overall Driving Behavior

7.1.3.1 Indicators of a Safety Benefit for ICC

Time-Headway - Time-headways were longer for the ICC system than manual driving, but less than CCC. Average time-headways for freeway driving were about 1.9 seconds for ICC compared to 1.7 seconds for manual and 2.2 seconds for CCC.

Velocity Variability (Freeways) - Variability in ICC velocity was much less than manual driving, but more than CCC. The average standard deviation in velocity was about 4.4 km/h for ICC compared to 11.1 km/h for manual and 2.8 km/h for CCC.

Acceleration - The spread of acceleration (positive and negative) was much wider for manual driving. Most of the ICC accelerations fell within +/- 0.05 g, whereas more manual accelerations fell outside this range.

Acceleration Variability - Acceleration variability for ICC driving was relatively low and less than that for manual driving for all velocity levels. The largest standard deviation in acceleration for manual driving was in velocities below 80 km/h.

Braking Frequency - The number of brakings per kilometer of freeway driving for ICC (about 5.0 brakings per 100 km) was significantly less than for manual (about 25.0 brakings per 100 km) and for CCC (about 12.0 brakings per 100 km). The number of brakings per 100 kilometers of arterial roadway driving for ICC (about 31.0 brakings per 100 km) was also significantly less than for manual (about 90.0 brakings per 100 km) and for CCC (about 41.0 brakings per 100 km).

Braking Force - The overall distribution of braking force versus braking frequency was significantly less for ICC than manual (generally by more than one order of magnitude) and was more comparable to CCC. For example, the relative frequency of 0.1 g brakings on freeways per 100 kilometers traveled (at velocities greater than 80 km/h and with lead vehicle present) was about 0.11 for ICC compared to 0.14 for CCC and 5.00 for manual. Although the proportion of brakings at force levels 0.1 g and higher is generally greater for ICC than for manual and CCC, the actual rate of brakings (brakings per million kilometers) in these higher force levels is consistently less for ICC than for manual.

The overall distribution of braking force versus braking frequency on arterials was significantly less for ICC than manual. However, the proportion of brakings at force levels 0.1 g and higher is generally greater for ICC than for manual and CCC. This latter finding is consistent with the concern expressed elsewhere that ICC drivers tend to wait for the system to control situations and, therefore, intervene later when necessary. Although this is a concern, the higher braking force events are extremely rare (only 39 braking events at 0.30 g or higher were detected for the ICC system on arterials).

7.1.3.2 Indicators that are Safety Neutral for ICC:

Velocity - ICC velocities tended to be less than CCC, but more than manual. Average velocities on freeways were as follows: ICC = 106 km/h, manual = 96 km/h, CCC = 110 km/h. The velocity differences were interpreted to be the result of the different traffic conditions under which drivers choose to drive manually or with cruise control. This measure was interpreted as indicating no particular benefit, or disbenefit, for ICC.

7.1.3.3 Indicators of a Safety Concern for ICC:

Response Time - Driver responses to brake light stimulus of a lead vehicle were generally longer in ICC driving than manual, by about 0.3 seconds, but slightly less than CCC. The longer response times in ICC (and CCC) appear due, in part, to longer time-headways for these systems and drivers taking advantage of these longer times to delay responding. Although, there was no clear evidence that the longer responses were due to inattentiveness, the possibility of inattentiveness cannot be ruled out for all situations. However, based on the video analysis as well as participant questionnaires and focus groups, drivers seemed to be well aware of evolving situations. In fact, a pattern emerged from the analysis suggesting that drivers with ICC tended to wait for the system to respond to given situations to avoid disengagement and, hence, intervened later than would be the case in manual operation. In general, the later interventions did not result in dangerous situations.

7.1.4 Driving Behavior in Safety-Critical Situations

7.1.4.1 Indicators of a Safety Benefit for ICC

Time-Headway (Freeways) - Time-headways in closing situations were slightly longer for the ICC system than for manual and CCC driving. Average time-headways for freeway driving were about 1.7 seconds for ICC compared to 1.5 seconds for manual and 1.6 for CCC.

Braking Frequency (Freeways) – During closing events, there were generally fewer brakings at each braking force level for ICC than for manual, although at force levels greater than 0.30 g the frequency was about equal.

State Space Boundary Crossings (Freeways) - The frequency of encountering critical combinations of headway and closing rate per kilometer of freeway traveled was much less for ICC than for manual and CCC. For example, situations that would have required the host vehicle to decelerate at a constant rate of 0.10g to avoid a minimum headway of 4 m with a lead vehicle was encountered with a frequency of about 4.0 per 100 kilometers for ICC in contrast to about 6.0 for CCC, and about 14.0 for manual.

Close Calls (Freeways) – This measure indicates the frequency of potentially dangerous interactions with other vehicles. The frequency of "close calls" on freeways per 100 kilometers traveled for ICC (3.4) was about half that for manual driving (6.2) and about equal to CCC.

Most Severe Close Calls (Freeways) – The frequency of the most severe category of close calls on freeways per 100 kilometers traveled for ICC (0.2) was substantially less compared to manual driving (0.5), but greater than for CCC driving (0.1).

Pre-crash Scenarios (Freeways) - ICC driving resulted in 45 to 70 percent fewer pre-crash scenarios than manual driving depending on the type of scenario, and about the same frequency as

CCC. Pre-crash scenarios analyzed included lane changes, cut-ins, approaches, and lead vehicle decelerations.

7.1.4.2 Indicators that are Safety Neutral for ICC

Closing Rate – The closing rate between the host vehicle and a preceding vehicle, during closing situations, was slightly lower for ICC than for manual or CCC on freeways. On arterials, the closing rate for ICC was slightly higher than manual. Overall, in terms of closing rate, the ICC system was considered safety neutral relative to manual driving.

7.1.4.3 Indicators of a Safety Concern for ICC:

Velocity (Freeways) – The mean velocity of ICC on freeways during closing situations was about 11 km/h higher than manual and about equal to CCC. The higher velocities for ICC, however, did not result in shorter headways or higher closing rates and, thus, an increased probability of a crash. Nevertheless, the velocity result was considered a safety concern since the severity of a crash, if it occurred, could be increased.

Braking Force (Freeways) – The proportion of brakings at higher force levels was higher for ICC than for manual at levels above 0.10 g. This is a safety concern for ICC as it indicates that during closings, braking with ICC was more apt to be harder than braking with manual or CCC.

Driver Response Time (Freeways) - Driver responses to the brake light stimulus of a lead vehicle, in critical situations of short headways, high levels of lead vehicle deceleration, and large velocity reductions of the host vehicle, were slightly longer for ICC driving than for manual, but slightly less than for CCC. Although the response times in ICC (and CCC) were longer, evidence from driver questionnaires suggests that ICC drivers are well aware of closing events and not inattentive, and results of the critical scenario and video analyses suggest that only in extremely rare situations do drivers wait so long that severe braking is required. The response time analysis is therefore viewed as a safety concern, but not an indication of a general safety problem for the ICC system.

Close Calls (Arterials) - ICC driving on arterial roadways generally resulted in greater rate of close calls than for manual or CCC driving. The average number of close calls per 100 kilometers of travel on arterials was over 5.0 for ICC and CCC, about 2.5 times that of manual driving. The high average rate of close calls when ICC was used was not representative of the majority of drivers who used ICC on arterials. Of those who used ICC on arterials, 40 percent had no close calls. However, a third of the drivers had an extremely high rate of close calls and raised the overall average to high levels. Although this is a safety concern, it is confined to a subset of drivers, and from the perspective of safety exposure, ICC was used only about 6 percent of the time when driving on arterial roadways. This was, therefore, not deemed a general safety problem for the ICC system.

Most Severe Close Calls (Arterials) – When analyzing only the most severe category of close calls, the same trend of higher ICC frequency for a subset of drivers on arterials was seen. The frequency of most severe close calls on arterials for ICC was about 2.2 per 100 kilometers traveled versus 0.9 for manual and 1.6 for CCC.

Critical Pre-Crash Scenarios (Freeways) –Video examinations were made of 41 events that had the highest braking levels or near encounters in the FOT. These 41 events were then classified into pre-crash scenarios groups. Of the 41 events, 20 involved driving with the ICC system, 14 involved use of CCC, and 7 involved manual driving.

All cases that indicated a safety concern for ICC resulted from drivers appearing to wait for the ICC system to respond to an evolving situation to avoid disengagement and then intervening late, braking at a high level, to successfully resolve the situation. This is essentially the same phenomenon noted above in the response time discussion. The video analysis concluded that, although the ICC driver may have contributed to the severity of situations by waiting longer to intervene, none of the situations indicated a general safety problem for the ICC system. It was also noted that the ICC situations may have involved a learning component; i.e., the ICC drivers were learning how best to use the system and that the critical situations noted might decline with more experience.

7.1.5 Driver Perceptions of ICC Safety

Field test participants, overall, ranked manual driving most safe, ICC next, and CCC least. However, drivers said they drove most cautiously with ICC and agreed that ICC would improve safety. Drivers also said they felt safe using the ICC system.

7.1.6 Estimated Safety Benefits of Widespread ICC Use

If ICC systems were to be fully deployed and used at the levels in the FOT, it is estimated that the number of collisions on freeways would be reduced by 17 percent for two specific types of collisions: (1) ICC vehicle approaching a slower vehicle traveling at a constant velocity, and (2) a lead vehicle decelerating in front of an ICC vehicle. Although not estimated under this current effort, additional safety benefits from ICC use would be expected from a reduction of other rear-end collisions involving cut-ins and lane changes, and from use of ICC on roadways other than freeways.

7.2 Evaluation Goal #2 – Evaluate ICC System and Vehicle Performance

7.2.1 ICC Sensors

The ICC sensors were able to detect vehicle targets within the specified field of view and were adequate for freeway conditions. The sensors also measured distances very accurately. The field of view extended to 133 m, but reliable detection of targets extended to about 100 m. There was some loss of targets on the curves and hills of secondary roads and ramps but not sufficient to degrade overall performance. In severe rain, the system automatically shut down, as designed, when backscatter from rain was excessive. The system did not perform well in snow because snow would accumulate on the bumper and sometimes generate false negatives as the snow scattered signals from the lead vehicle. In other instances, the snow on the bumper would generate false positives as it reflected signals directly back to the sensors. Because of its prototype status, these are understandable performance problems, but would need to be addressed prior to commercialization.

7.2.2 ICC Driver Interface

The driver interface was generally well received by participants. The low visibility buzzer, indicating sensor backscatter during rain and snow, was found annoying by some.

7.2.3 Integrated ICC and Vehicle Performance

As a prototype, the ICC system performed remarkably well both in a variety of controlled experiments on public roadways and under natural conditions driven by the FOT participants. Analysis of the FOT data shows that the ICC system adequately maintains set headways and velocities, and reduces the need for drivers to brake within the control authority of the system. There were performance problems when the system was operated in rain or snow. However, these problems were not regarded as serious because they appeared related to the prototype status of the system. The system was less aggressive in accelerating to close gaps than in decelerating to extend gaps. This tended to increase headway gaps beyond the set headway. Drivers noted that they would have desired more acceleration capability.

7.3 Evaluation Goal #3 – Evaluate User Acceptance of the ICC System

The FOT participants expressed a strong level of acceptance of the ICC. Both prior users of CCC and non-users of CCC preferred the ICC to CCC. Participants overwhelmingly ranked ICC over CCC and manual for convenience, comfort, and enjoyment.

Participants, particularly those who had the ICC system for only one week, indicated that they would be more comfortable with the system given more time. This indicated that ICC driving introduced a sufficiently new dimension to driving that the participants required more than a week of experience to be fully comfortable with the system. This suggests that special orientation and training of future ICC users might be appropriate.

Participants indicated they would most likely use ICC on freeways, however, a significant number would also use it on 2-lane and rural roads where they indicated they were comfortable using it. This suggests that future ICC systems should be designed with their use on secondary roads in mind (for example by accommodating narrow lanes, sharp curves, and steeper hills).

There was a high level of comfort in seeing ICC replace CCC in future vehicles and median estimates of willingness to pay ranged from $275.00 by those who do not use conventional cruise control, to $475.00 by current users of conventional cruise control.

7.4 Evaluation Goal #4 – Evaluate System Deployment Issues

7.4.1 ICC Effects on Traffic Flows

Under certain conditions of short time-headway settings (e.g., 1.0 second) and high velocities, ICC systems could improve roadway capacity. Longer time-headway settings (e.g., 2.0 seconds) could reduce roadway capacity. Alternative, non-linear time-headway control algorithms could improve roadway capacity beyond that of the tested system. Also, alternative algorithms could reduce the impact on traffic flows of instabilities caused by multiple ICC equipped vehicles traveling in platoons.

7.4.2 ICC Effects on Fuel Consumption and Emissions

Use of the ICC system reduces throttle fluctuations and, thus, the frequency and magnitude of accelerations. These factors will result in reduced fuel consumption and emissions for ICC driving.

7.4.3 Projected ICC Costs

Projected costs of ICC systems at 500,000 units per year fall within the range of the average willingness-to-pay of between $275 and $475 determined from the participant questionnaires.

7.4.4 Institutional Issues

The study identified two issues directly relevant to future deployment of ICC-like systems: (1) ICC standards and (2) instruction of new ICC users. Participants indicated that the Government should be involved in developing standards for these systems and that the lack of standards for ICC technology might adversely affect their development. Also, there was some consensus that the development of instructional materials would be useful to help ensure that new users of ICC operate the system appropriately.

7.5 Recommendations

Beyond the conclusions discussed above, the following additional recommendations are made for further consideration:

7.5.1 Safety Effects of ICC Systems

7.5.1.1 Further research into ICC systems with higher deceleration authority seems warranted. Systems with braking authority up to a range of 0.2 g to 0.3 g would automatically resolve all but the rarest of events observed in the FOT. Such systems would eliminate most of the situations where the driver waited for the system and then had to intervene late to exercise additional braking. The dilemma such a system creates, however, is that the driver may become over-reliant on the system and may not be prepared to intervene in extremely rare situations (even beyond those experienced during the FOT) when intervention is required. Research in this area should, therefore, also include the need for supplementary driver warnings, control algorithms for effective ICC control in braking situations, and human factors issues.

7.5.1.2 As was observed in the FOT, use of the ICC system on roadways other than freeways, such as arterials, created some safety concerns. Techniques to mitigate potential hazards of using ICC on non-freeways should be investigated. Possible solutions might involve development of instructional techniques for new ICC users, means for inhibiting the operation of ICC on non-freeways, and/or tailoring the performance of ICC systems to meet the unique operational requirements of non-freeway driving.

7.5.1.3 Use of the ICC seemed to place new demands on the driver that required some time for drivers to adjust to. This was noted in the driver questionnaires, the institutional analysis, and in observation of videos. A concern this raises is that new drivers could use the system in ways that is inappropriate and potentially hazardous. Development of effective techniques for orientation and training of new ICC users to assist in the learning process is therefore suggested as an area of future research.

7.5.2 ICC System Performance

7.5.2.1 Marketable ICC systems should address shortcomings identified in the FOT, particularly the effects of snow. In addition, to the extent that ICC will be used on secondary roads, the systems will need to function well under these more difficult roadway geometries.

7.5.2.2 The combination of the video and digital data collected for this evaluation provides a basis for conducting reliability-based measurements and quantitative analyses. The video data could serve as the truth against the digital data for determining vehicle identification, tracking, and validation performance.

7.5.3 Deployment Issues

7.5.3.1 More research is needed on the effects of wide-scale deployment of ICC on traffic flows. In particular, the effects of time-headway settings, algorithms for controlling headways, and multiple ICC vehicles in platoons on traffic flows should be investigated.

7.5.4 Supporting Research

7.5.4.1 The ICC FOT produced extensive data on the performance of the ICC system, as well as the manual driving characteristics of a variety of drivers under a range of ordinary traffic conditions. This is extremely useful information for researchers and system developers. The data from the ICC FOT should be made readily available to the public in a format that is convenient to support a wide range of uses.

7.5.4.2 To support the ICC evaluation, a number of data processing and analysis tools were developed. These include a Driving State Identification Tool, a GIS/GPS Map Matching Tool, a Congestion Model, and a Video/Digital Data Integration Tool. The later tool includes a comprehensive data set of over 10,000 video driving events (with and without cruise control) from the FOT. These tools are fully documented in this study and should be made available to the public to support related research.

7.5.4.3 A problem faced by the researchers with regard to the video data was determining what events should be saved for analysis. There was a storage capacity that precluded saving all the continuous videos. An algorithm was therefore developed to identify and prioritize video clips to be saved for future analysis and is described in this report. It is recommended that future researchers build on this algorithm to meet their specific needs. The algorithm used had the advantage of providing a mix of data from both freeways and arterials. The form of the algorithm and the parameters used may be adjusted to focus on particular areas.

7.5.4.4 An extremely challenging technical problem that confronted the evaluators was to develop techniques for identifying driving scenarios (e.g., cut-ins, lane changes, approaches, and lead vehicle decelerates) from a stream of digital data. Significant progress was made, but further research is required to perfect and standardize the techniques to provide a uniform means for evaluating future collision avoidance systems. The scenarios can serve two purposes. First, as a dependent measure, the rate of occurrence of the scenarios may be an indicator of the collision risk. Sufficient data was generated during the FOT to test this hypothesis for normal driving, that is, driving in the manual mode as opposed to the cruise control mode. Available collision rates for different roadway types could be examined, for example, with respect to the measured pre-crash scenario rates.

7.5.4.5 One of the tools mentioned above was an algorithm that was developed to determine driving states and transitions. These driving states and transitions were then related to specific maneuvers for the purpose of this evaluation. These states and transitions, since they are general descriptors of driving situations, should be used by future researchers to identify other scenarios or circumstances that may be needed in field test evaluations.

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