Comparing Driving Behavior for Manual, Conventional and Automated Cruise Control Driving in Car-Following by Scenarios Based on an Advanced Driver Performance Map

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ABSTRACT

Every year more than six million crashes occur in the USA, killing over 40.000 people and causing more than three millions of injuries [7]. A major part of these crashes are rear-end collisions. Therefore the U.S. Department of Transportation has put a lot of effort in fostering the development of rear-end collision avoidance systems by funding governmental, academic and industrial research groups in the last ten to fifteen years. The intelligent cruise control field operational test (ICC FOT) [1, 4] represents an important milestone in this line of research. With its various findings and its big amount of recorded data it is a valuable means for evaluating the impact of automated cruise control systems (ACC) on driver performance.

This paper addresses the safety-enhancing potential of the ACC system in the ICC FOT. For the comparison of manual, conventional cruise control (CCC), and ACC driving behavior in car-following scenarios during the ICC FOT a novel performance map [5] was applied. This map associates the exposed driving behavior with four driving states: low risk, conflict, near crash, and crash imminent. The transition boundaries between the low risk and conflict state and between the conflict and near crash state are based on the drivers' braking and steering responses in last-second evasive maneuvers of test track trials [2].

For a complete evaluation, a theoretical boundary between the near crash and crash imminent states derived from vehicle dynamics will be introduced. Subsequently, by the means of this advanced driver performance map, an evaluation of the safe driving performance of different driver groups with and without ACC and CCC deployment will be shown. An analysis of the findings concludes this paper.

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INTRODUCTION

In the ICC FOT a prototype ACC system was investigated for its functionality and then used in a comprehensive field test by 108 lay-drivers [1, 4]. In the follow up analysis of the ICC FOT, the University of Michigan Transportation Research Institute (UMTRI) classified the participating drivers by their manual driving behavior and then compared this to the behavior with an engaged ACC system or an engaged CCC system, which was also available in the field test.
In this paper the safety evaluation of the driver behavior exposed in the ICC FOT is related to pre-warning horizons. Therefore, a classification scheme is employed and advanced that distinguishes driver behavior in driving states corresponding to the warning levels of a forward collision warning (FCW) system.
Since the end of the ICC FOT several other test series were carried out (for instance the CAMP project [2, 3]), which applied evaluation methodologies focused on human factor studies. Thus, reasonable thresholds between the different safety levels of driver behavior in car-following scenarios could be derived in follow up analyses and evaluations ([3]-[6]). These classification schemes are the tools most suited for evaluating driver behavior in the intended way.
The one chosen here is a map of driver performance that was developed by Najm, Lam, and Smith ([5] and [6]) to characterize driver behavior in car-following scenarios. This approach evaluates driver performance independently of the driving environment; in other words, it is thought to be an objective characterization tool for simulation, test track, and on-road studies.
In the following, this driver performance map will be explained in detail. Subsequently, the data filtering and associating process is described in brief. Then, this driver performance map is applied on the ICC FOT data. The results and findings are finally analyzed for the different driving modes.

ADVANCED DRIVER PERFORMANCE MAP

The performance map consists of four different safety-related driving states: low risk, conflict, near crash, and crash imminent ([5] and [6]). The boundaries between the different states were quantified by the recorded data from the first CAMP test track studies (cf. [2]). In the CAMP test series baseline tests were conducted to understand drivers' last-second braking performance. Drivers were advised to perform an evasive braking maneuver in the last possible moment either in a normal or a hard way. Additionally, there were trials carried out to collect data of a last-second steering performance similar to the braking trials. By the normal and hard last-second braking/steering maneuvers of the participants, the transition thresholds between the low risk and conflict state and between the conflict and near crash state were determined, respectively.
In the work of Najm, Lam, and Smith boundaries for lead vehicle stopped (LVS) and lead vehicle moving (LVM) scenarios were developed. Here, only the LVM boundaries will be applied, because the investigated ACC system only detects and tracks moving lead vehicles [2]. They also found out that the average last-second braking response is

independent from the average last-second steering response. Consequently, there are two different sets of driving state boundaries. These boundaries are based on scenarios where the lead vehicle was traveling at a constant speed and the following vehicle was closing in with higher constant speed, until last-second braking/steering was initiated. Thereof several tests with different initial relative velocities were carried out to obtain a relatively complete set of data in the range vs. range-rate plane. Out of these data clouds, the 50%-iles of the driver responses of these scenarios were determined.

The boundary between the near crash and crash imminent state understandably could not be determined in these test track studies. Therefore, a theoretical boundary is introduced here to complete the performance map. Equation (1) denotes the minimum range r when the following vehicle has to initiate braking with a constant deceleration rate a to avoid an impending collision while closing in with a constant relative velocity (range-rate) Δv :

$$r = 0.5 \, \frac{\Delta v^2}{a} . \tag{1}$$

This equation is derived from inter-vehicular dynamics, given the same initial conditions as in [5], [6]. In the safety evaluation statistics a value of a=8m/s^2 was used, so this threshold characterizes a real emergency situation.

There was no corresponding boundary chosen for the steering case, because equation (1) was meant to indicate very dangerous situations in all car-following scenarios, not only for the braking case.

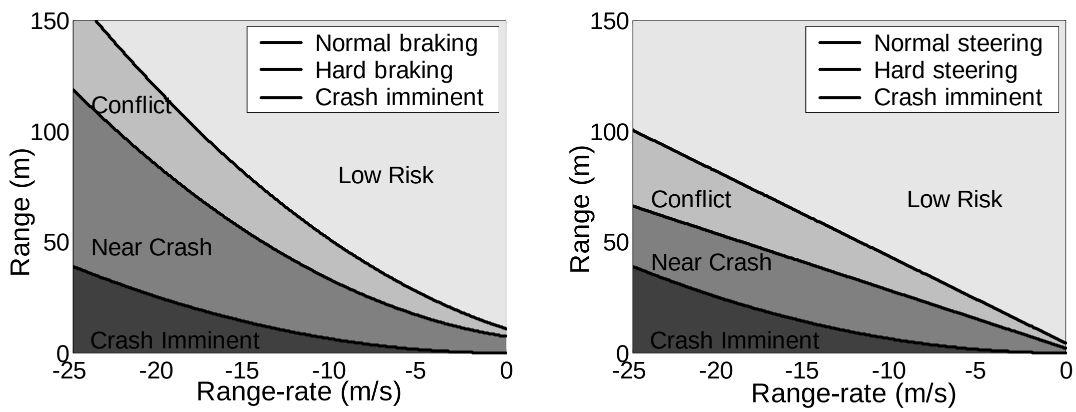

Figure 1: Boundaries of the performance map in the range vs. range-rate plane. *Left:* The state boundaries describing the last-second braking response. *Right:* The state boundaries of the last-second steering response.

The transition boundaries are shown in figure 1. The left plot describes the last-second braking response, the right plot represents the last-second steering response. The dash-dotted lines denote the boundary between the low risk and the conflict state that corresponds to the last-second normal response and the dashed lines symbolize the boundary between the conflict state and the near crash state that corresponds to the last-second hard response, respectively. Recall that the near crash/crash imminent boundary is not directly related to one of the two cases. It is a theoretical boundary for a more detailed evaluation of the driver performance in the following safety evaluation statistics.

A comparison of the two plots reveals that the transitions in the steering case generally occur at smaller ranges than in the braking case. This difference between the two scenarios is a consequence of the vehicle dynamics and of the attempt of matching the velocity of the preceding vehicle in the braking case. Drivers normally do this in a moderate way without the use of emergency braking.
The braking response also shows that a FCW system, based on TTC only, cannot match the drivers' perception of the different driving states in an adequate manner, because it totally neglects the inter-vehicular dynamics. Therefore, by applying the transition boundaries of the performance map, the safety evaluation statistics of this project evaluates driver behavior in a more realistic way.

FILTERING AND ASSOCIATING OF THE RELAVANT DATA

During the ICC FOT data were recorded of each of the participating drivers [1]. These data contained measures (e.g. range, range-rate, velocity of the equipped vehicle, etc.) as well as modes (e.g. ValidTarget, ACCmode, etc.) describing the state of the equipped vehicle in the current traffic situation and were recorded with a frequency of 10 Hz.
In the evaluation of the driving behavior only data records were considered to be relevant in which the host vehicle's velocity v was higher than 35mph and the relative velocity Δv was negative. The first constraint was chosen because only at velocities above 35mph the ACC system could be enabled. Thus, a reasonable comparison of the different driving modes can only be drawn in the same velocity span. And second, only for negative relative velocities, when the following vehicle closes in, critical situations can emerge.

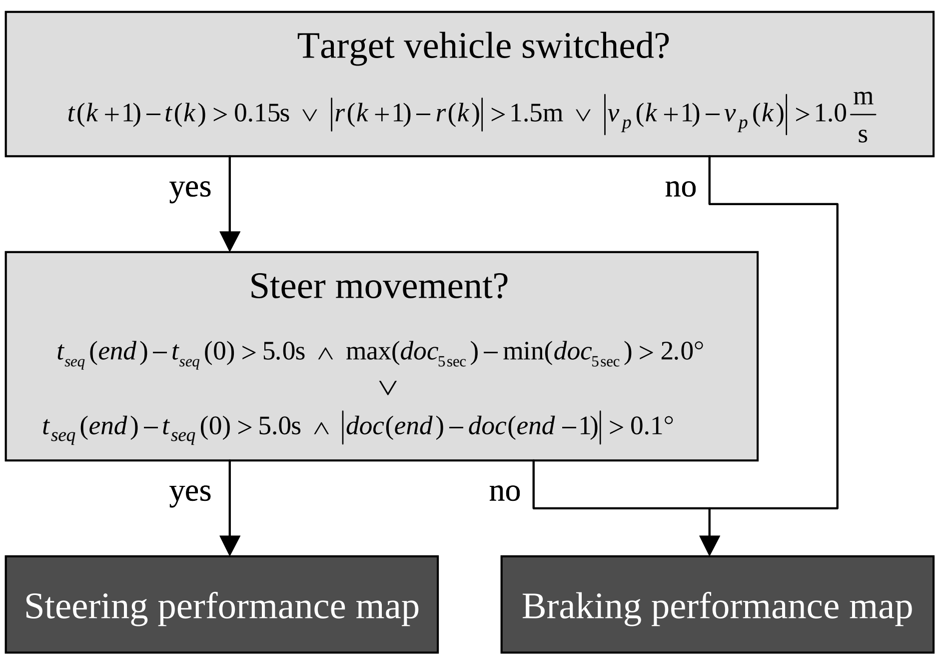

Figure 2: Flowchart of the algorithm for identifying steering movements prior to a target vehicle switch.

After the filtering of the relevant data records, these were associated to either the braking performance map or the steering performance map by an algorithm (cf. figure 2) that recognizes a steering movement prior to a switch of the preceding vehicle (target vehicle).
The first inquiry in the algorithm determines if the target vehicle stayed the same or if it changed from one time step to the next. Therein $t(k)$ denotes the recorded time, $r(k)$ the range, and $v_p(k)$ the velocity of the preceding car at any given time step k. So, if the difference of the recorded time between two subsequent time steps is bigger than 0.15s, there was an interruption of the data stream with the current preceding vehicle. If the differences in the range r or velocity of the preceding car v_p exceed their thresholds the target vehicle cannot be the same as in the time step before, because the required acceleration/deceleration rates are physically not achievable with normal cars. Hence, these three thresholds indicate a target vehicle switch.
The second inquiry examines if there was a lane change prior to a switch. This inquiry is a simplified version of a lane-change algorithm developed by Volpe [4] and was adjusted according to the last-second maneuver boundaries. Therein, the maximum and minimum value and the variation in time of the degree of curvature *doc* are investigated in a time window of five seconds prior to the switch. When the criteria in both inquiries are satisfied then a lane change can be assumed with a high probability.
After associating the data records to the corresponding performance maps, they were allocated to the different levels of safety.

ANALYSIS OF DRIVING STATES

For the comparison of the driver behavior in the different driving modes altogether 14,220,867 data records were analyzed. After the filtering and associating process a composition of all of these data records was found corresponding to numbers listed in table 1.

Driving mode	Manual, v>35mph	CCC, v>35mph	ACC, v>35mph
Time steps in braking case	9,695,474	1,638,356	2,319,014
Time steps in steering case	510,465	7,578	49,980
Time steps total	10,205,939	1,645,934	2,368,994

Table 1: Composition of the investigated data records in terms of time steps in the different driving modes.

There can be seen a tremendous difference in the number of time steps between the braking case and the steering case for all three driving modes. One explanation is that the algorithm for identifying steering movements was intended to associate the data records to the steering case only if a lane change can be assumed with a high probability. The thresholds used in the inquiries imply relatively strong steering movements. Lane changes in curves or with slight steering movements will probably not be identified. However, this problem is not too grave, because the transition boundaries of the performance map stand for last-second maneuvers, thus, they correspond to strong movements. Hence, the safety evaluation presented here points out consolidated tendencies in driver performance.

The percentage of time steps in the steering case relatively to the total time steps differs strongly between the driving modes. In manual driving it is approximately 5,3%, while in ACC ($\approx$2,1%) and in CCC ($\approx$0.5%) it is significantly smaller. This indicates that less lane changes were carried out in ACC and CCC driving compared to manual driving. Fewer lane changes lead to a harmonization and stabilization of traffic flow and thus, fewer critical situations emerge.

The analysis of the data records with the driver performance maps revealed a considerable enhancement in the safe following behavior when driving in ACC or CCC mode. Figure 3 depicts these enhancements.

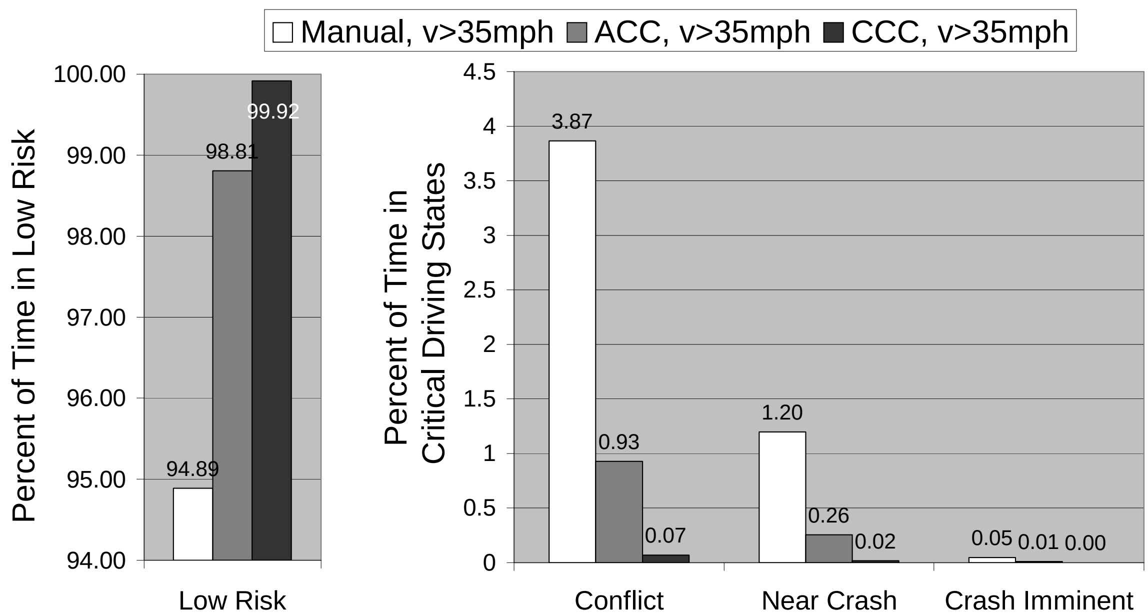

Figure 3: Comparison of the percent of time in the different driving states in every driving mode for all drivers.

At first sight, a percentage of nearly 95% in low risk situation in manual driving seems to be already quite high, but this also means that in more than five out of hundred seconds while closing in, drivers find themselves in critical situations. The ACC system already reduces these situations by almost four percent; so about 99% of the time drivers were closing in without getting too close. This corresponds to a reduction of approximately 80% of such critical situations.

In an examination of the performance in CCC mode, the proportion of low risk is even higher. This is surprising, considering that CCC is just a limiter without the property of adapting to the lead vehicle's speed. This high percentage obtained here will be put into perspective in the later analysis of the CCC driving performance.

Most of the 5% of critical situations in manual driving are in the conflict state. The situations can be solved by a normal to hard evasive maneuver. But in over one percent of the time while closing-in, drivers get into real hazardous situations, where an impending

collision can only be prevented by a hard evasive maneuver such as an emergency braking. The theoretical transition boundary between the near crash and the crash imminent state was invented to describe such an emergency braking. As we can see this boundary was passed a few times, too. Luckily, during the ICC FOT no collision was reported, so these situations can be explained by the fixed initial conditions from which the boundary was derived. Apparently, there occurred situations in which the inter-vehicular dynamics (e.g. strong acceleration of the preceding car with strong deceleration of the following car at the same time) permitted to close in onto the preceding vehicle with a higher relative velocity than was stated by the boundary.
The ACC and CCC modes display a similar ratio of approximately 1/3.5 as in manual driving between the percent of time in conflict and near crash state. Due to the high percentage of the low risk state in these two driving modes the percentages of the conflict and the near crash state are considerably smaller. The crash imminent state also occurred in the ACC mode, but very rarely. In the CCC mode not a single time step out of more than one-and-a-half million time steps was counted in the crash imminent state.

For the statistics the difference in driving performance in the diverse driving modes of a single driver is of less interest than to find differences in the performance of categorized driver groups. Hence, the driver groups determined in the ICC FOT [1] also are employed here. And since the critical driving states are only rare events, the focus is on the low risk state, cf. figure 4.

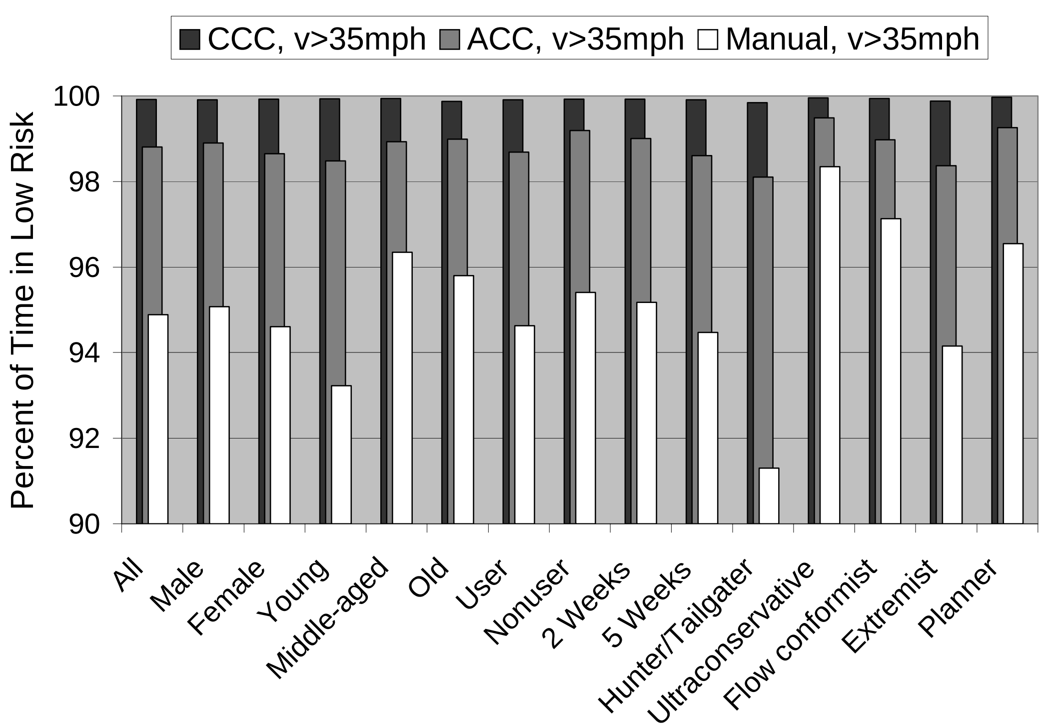

Figure 4: Comparison of the percent of time in the low risk state in every driving mode for different driver groups.

In a comparison of all different driver groups the performance in ACC and CCC stays relatively the same for all groups, whereas in manual driving the variation is a lot higher. On the one hand, there are no big differences recognizable between male and female drivers, users and nonusers, and between the groups with different durations of participation. On the other hand, the performances among age groups vary substantially. The younger drivers were driving significantly more risky than middle-aged or older drivers. Furthermore, the comparison of the last five groups back the findings of the UMTRI driver evaluation (cf. [1]). The drivers, who were identified as hunter/tailgater, showed the most critical average driver behavior. The extremists exhibited a comparatively normal low risk driving style, while the planners and the flow conformists revealed an enhanced safely behavior in accordance with their characterization. The ultraconservative drivers exhibited the most secure driving style.
In general, the ACC mode exposes the same tendencies for the driver groups like in manual driving, with the important difference that the percent of time in the low risk state stayed over 98% for all driver groups, even for the most risky driving groups young and hunter/tailgater. The CCC performance remains above 99,8 % for all groups, thus, no noteworthy differences can be seen.

ANALYSIS OF DRIVER PERFROMANCE

The statistical values of the previous section will be explained here on the basis of the driver performance in the range vs. range-rate plane (cf. the braking/steering performance maps). Proceeding from the manual braking performance, we will draw comparisons to the ACC and CCC braking performance, respectively, to examine in which area of the range vs. range-rate plane the safety benefits were achieved. A depiction of the steering case is renounced, since the vast majority of data records was associated to the braking case.
For an analysis, it is necessary to find a graphical representation that makes it possible to realize where in the range vs. range-rate plane the several millions of data records are located. A plain depiction of the data clouds in the range vs. range-rate plane turned out to be unsuitable. Hence, a three-dimensional histogram was created (cf. top left plot in figure 5).
The range vs. range-rate plane is rasterized into rectangular bins. In the direction of range a bin length of 2.5m was chosen, in the range-rate direction the bin width amounts to 1m/s. Then, the number of data records in every rectangular bin is counted and presented in form of a square stone on top of one bin. The height of such a square stone corresponds to the number of data records that lie in the affiliated bin and is referred to as frequency of occurrence.
Most of the time in following a preceding vehicle, drivers match the velocity of the preceding car quite well and stay in a certain range, with the result that the biggest proportion of recorded data are in the rightmost bins on the range-rate axis at a range of 20m to 50m. Hence, close-ins with a high relative velocity and especially at an additional close range are very rare events. Given that the critical driving situations occur in these areas, a depiction in a logarithmic scale to the basis of ten was used for a better recognition of the frequency of driving states in these critical regions.

For a more comprehensive depiction, the top right plot in figure 5 shows a top view of the frequency of occurrence for the braking case. The gray-level of a bin is related to its height. The lines denote the transition boundaries between the different driving states, as introduced in above. Despite the fact that the range vs. range-rate plane is rasterized now, the lines are a helpful means to understand which bins belong to which driving state and where the most critical situations emerged.

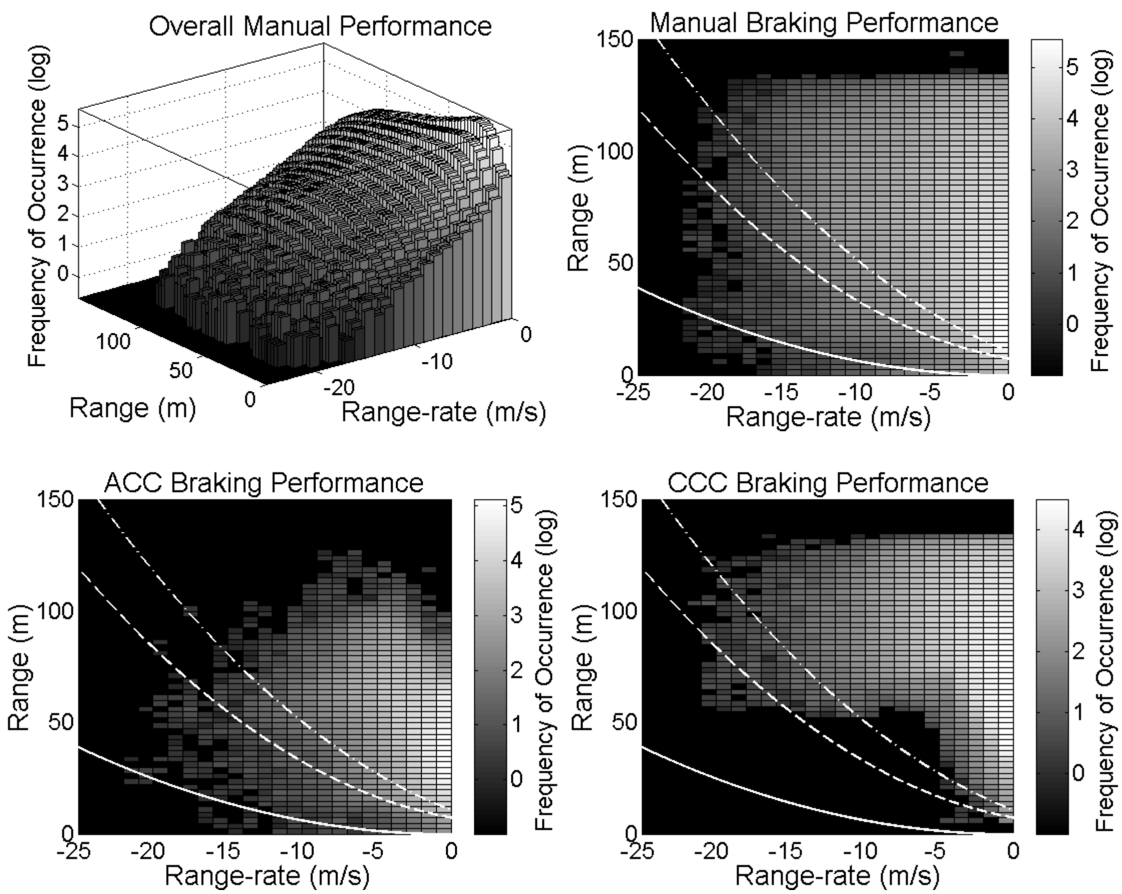

Figure 5: Frequency of occurrence (log) of data records in a rasterized range vs. range-rate plane. *Top left:* The frequency of occurrence of the overall manual driving in a three-dimensional depiction. *Top right:* Top view of the manual braking performance. *Down left:* Top view of the ACC braking performance. *Down right:* Top view of the CCC braking performance. The lines in all three top view plots denote the transition boundaries between the different driving states, respectively.

The data records for manual braking performance occurred in nearly the whole portrayed range vs. range-rate plane. light colors represent bins in which the most data records were found. As can be seen, these bins are the rightmost bins on the range-rate axis in a close to middle range. In these situations, apparently drivers tend to follow at such a close range that they frequently enter the conflict and even the near crash state. Thus, it can be stated that the most critical situations occurred at small relative velocities. That means drivers were not matching the lead vehicle’s speed in an appropriate way while following. It can be assumed that these situations are often elicited by driver inattentiveness or distraction.

In the short-range region and then going left on the range-rate axis, it can be seen that still some data records were found in high-risk states. According to their frequency of occurrence, they are rare events.

The black bins describe areas in which no data record was found. The sharp transition between the black and the dark bins at a range of approximately $r = 135\text{m}$ illustrate the maximum detection range of the sweep sensor of the ACC system.

Hence, the biggest potential in reducing critical situation lies in the small relative velocity region of the braking case.

The ACC performance, illustrated in the down left plot of figure 5, shows some similarities but also some remarkable differences to the manual performance.

Despite the fact that for the ACC performance only a fifth of the data records of manual driving could be analyzed, the tendency of covering a huge area in the range vs. range-rate plane is identifiable. That means in ACC driving all different driving situations occurred. Most of the data records again lie in the rightmost range-rate bins, at a longer range though. On the other hand, extreme long ranges never were recorded. Both are results of the ACC system's time-headway settings. The average time-headway in ACC driving was longer than in manual driving according to [1]. The most significant difference is the reduction in the high risk states. When we compare the crash imminent state and the near crash state of the ACC braking performance and the manual braking performance, it looks like the ACC performance is shifted in direction of longer range by two or three bins. Especially at small relative velocities, the number of critical situations decreased clearly.

The CCC driving performance, depicted in the down right plot in figure 5, is totally different from the previously analyzed two. The quadrant down left in the range vs. range-rate plane is completely deserted. When drivers were closing in with a high relative velocity they disengaged the CCC by applying the brakes at sufficient range, due to CCC's limiter property. The following critical data records were then associated to the manual driving performance. This system is not made for adapting the velocity, consequently it is not capable of doing it, and drivers are aware of that. Phenomena like the range coverage as far as to the maximum range, or the peak of the frequency of occurrence at ranges of about r = 50m and more, are results of the CCC system's limiter property and its field of deployment.

CONCLUSIONS

After the comprehensive presentation of statistical numbers and the detailed analysis of the driving modes in the previous sections, several conclusions concerning the comparison of all three driving modes can be drawn.

The enhancement of safety by the ACC system is evident in every measure investigated. In ACC driving mode, the percent of time in low risk situations was increased by about four percent. Pertinent to critical situations, this means that up to 80% of such situations could be avoided by such a system. Also, the difference in the number of braking and steering states indicates that lane-changes were reduced as well in ACC driving. Another

point worth mentioning is that even such driver groups like the hunter/tailgater group or the young drivers, which tended to an aggressive manual driving, experienced a considerable more safe overall performance. All these points are synonymous with a harmonization and stabilization of traffic flow.
The values and numbers presented here are remarkable and very much support the statement that the ACC system is not only a stress relief and safety gain for the driver of the ACC-equipped vehicle; from its widespread deployment drivers in the surroundings would also benefit.
In the comparison of the performance in the range vs. range-rate plane we found that the ACC performance is similar to the manual performance. The differences discovered are mostly due to the time-headway settings. The ACC system provides additional range and therefore shifts the whole driver performance in a safer state. The overall performance of the ACC system is even more impressive, when we consider its prototype status.
The CCC system revealed an even more safe overall performance. About 99.8% of all the time is spent in low risk state, which is absolutely astonishing at first sight. However, this phenomenon is a consequence of the very long ranges when it was employed. And if a critical situation emerged, then the drivers disengaged it early enough. The driver groups showed the fewest variations in CCC driving concerning the statistic values as well as the performance in the range vs. range-rate plane. The CCC system is not capable of matching a manual driving performance. It elicited a totally different driving behavior than in manual driving, which is due to the fact that the CCC system is a limiter system and, thus, it is used only in corresponding traffic situations, namely in light traffic.

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