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Driving Characteristics and Adaptive Cruise Control – A Naturalistic Driving Study

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***Abstract*—With the increasing number of vehicles equipped with Adaptive Cruise Control (ACC), it becomes important to assess its impact on traffic flow efficiency, in particular with respect to capacity and queue discharge rate. Simulation studies and surveys suggest that ACC has both positive and negative effects on traffic flow, but empirical evidence on this topic is scarce. A naturalistic driving study has been conducted with 8 participants who drove their own ACC-equipped vehicle during their regular trips on freeways for a period of 4 to 5 weeks. We measured spacing, headway, speed, acceleration, lane use, and the number of lane changes, and compared these between ACC On and ACC Off in different traffic states, for a total of 48 hours of driving data. Results show that with ACC On, average spacing and headways were larger, whereas standard deviations were smaller. Larger headways can be assumed to reduce capacity, whereas more constant spacing, headway, speed, and acceleration indicate more stable traffic. With ACC On, drivers performed 36% fewer lane changes in saturated traffic, resulting in increased use of either the faster or the slower lane, depending on the driver. Furthermore we found that headways were smaller with ACC On than ACC Off when only selecting accelerations below -0.5m/s^2 and above 0.5m/s^2, which is the opposite of the overall finding. The latter result suggests that ACC has an important limitation: a lack of anticipation. On the other hand, the smaller headways with ACC On during acceleration indicate an increased queue discharge rate.**

***Index Terms*—Adaptive cruise control, traffic flow efficiency, capacity, queue discharge rate, anticipation.**

I. Introduction

IN the development towards automated driving, a first step has been the introduction of Adaptive Cruise Control (ACC) in consumer cars. The deployment rate of ACC has been steadily growing in the past years and is now approaching 5% of newly sold cars [1], [2]. ACC maintains a set speed similar to a cruise control system, and additionally responds to a predecessor by maintaining a set headway.

In this paper, we focus on driving characteristics related to traffic flow efficiency, that is, those factors that affect travel time. ACC may have opposing effects on traffic flow efficiency. On the one hand, ACC has been found to increase headways compared to driving without ACC (e.g., [3]). The larger the headway setting, the more space between vehicles at the same speed and thus the lower the roadway capacity. On the other hand, driving with ACC is expected to result in more stable traffic, as it reduces fluctuations that otherwise arise due to imprecise control of speed and headway by human drivers. For at least some penetration rates, breakdown of traffic might consequently be averted, so that ACC could actually increase traffic flow capacity. A literature study on the possible effects of ACC (as well as more highly automated systems) on traffic flow efficiency was recently conducted [4]. This study pointed out that human factors are crucial in assessing the effects.

Most research on the effects of ACC on traffic flow efficiency has been based on computer simulation studies. A simulation study showed that for capacity to increase, the ACC has to be set to a headway of 0.8 s or smaller [5]. Others have reported that capacity benefits occur only if ACC is active at all speeds and if the penetration rate is at least 20% [6]. The effects of ACC on traffic flow stability have also been investigated in simulation studies. It has been found that speeds and headways are more constant when ACC is used [7], and that traffic flow stability strongly depends on the settings of ACC [8].

The use of ACC may also affect lateral behavior. A focus group study [9] found that drivers with ACC were inclined to perform fewer lane changes. Rather than overtaking, participants indicated to stay in the slower lane and let ACC follow the predecessor. This was also found in a study with both a naturalistic driving study and another focus group study [10].

Queue discharge rate is another important factor that affects travel time. It is a well-known fact that human drivers in congestion drive with long headways relative to free flow driving [11]. In [11] it is mentioned that ACC could contribute to congestion reduction, because it might compensate the increased headway that human drivers show in congestion. In [12] an ACC is developed where the settings depend on the traffic state, thereby increasing both capacity and queue discharge rate in their simulations. By means of simulations, it has been shown that at sags, ACC is able to reduce travel time [13]. Specifically, an evaluation of the behavior of individual

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Fig. 1. Installed cameras, pointed at the dashboard (left) and behind the rear-view mirror (right).

vehicles showed that ACC-controlled vehicles reduce headways when accelerating from a sag, an effect which is then partially transferred to non-ACC-controlled followers. In [13] different ACC systems were evaluated, including systems where settings were adjusted to the traffic state. A comparison of different settings showed that reducing the headway at the end of the congestion (i.e., increasing the queue discharge rate) is important for reducing travel time.

The question arises to what extent the results of computer simulations correspond to actual ACC systems. The validity of simulations may be limited because traffic models have a particular difficulty in reproducing the differences between humans and ACC as both agents are modeled using similar control laws [14] and human factors are not included [4]. Research in driving simulators and on the road indicates that headways increase with the use of ACC [3], [10], [15], [16], [17]. On the other hand, speeds and headways are found to be more constant with ACC than without [3], [17], which suggests that ACC improves traffic stability. Furthermore, ACC is found to increase safety, and therefore reduces congestion due to incidents [3], [17].

Empirical evidence on the effects of ACC on driving characteristics and traffic flow efficiency remains scarce. In this paper, we present results of a new naturalistic driving study on freeways with 8 participants in order to obtain empirical insights into changes of driving characteristics that ACC introduces. Participants drove their own car and were therefore used to the ACC system. With this study we empirically evaluated the inferred impact of ACC on traffic flow efficiency. Specifically, we investigated capacity, stability, and queue discharge, and focused on the dynamic relation between headway, spacing and acceleration (i.e., the responses at considerable speed difference with the predecessor). The behaviors of humans (i.e., ACC Off) and ACC were compared. Results show that with ACC On headways increase, pointing to reduced capacity. Standard deviations of spacing, headway and acceleration, and the number of lane changes, reduce, inferring more stable traffic. The dynamic relation between headway, spacing and acceleration suggests that ACC increases queue discharge rate, while also indicating that a lack of anticipation is an important shortcoming of ACC.

II. Experimental Setup

A. Equipment

To measure speed and acceleration an OBD2 logger (CarChip Pro) was connected to the vehicle CAN. Two Ambarella Mini 0801 cameras were used. One camera was pointed at the dashboard to monitor the ACC On/Off status indicator, and another camera was mounted behind the rear-view mirror in order to determine headway and the driving lane. The camera equipment was small (7x4x4 cm camera on a 3x3x2 cm base) and largely out of view of the driver, as can be seen in Fig. 1. The measurement equipment switched on and off automatically with the engine. Thus, the equipment did not influence driver behavior.

B. Measurement Data

Table I shows the data that were obtained, including the corresponding measuring equipment. The spacing (i.e., the distance between vehicles in meters) was determined with the forward-facing camera. A practical approach for determining spacing has been adopted. Upon installing the forward-facing camera, pylons and tape-measure equipment were used to establish where in the camera image the boundaries are of 8 spacing categories. The boundaries were put at 0, 5, 10, 15, 20, 30, 40 and 50 m from the front bumper. Category 1 has spacing $h > 50$ m, whereas category 8 has $0 \text{ m} < h < 5$ m. From the video footage with pylons in a stationary situation, a video overlay was made (Categories 2–8 correspond to 45, 35, 25, 17.5, 12.5, 7.5, & 2.5 m, respectively). The overall coding scheme is shown in Fig. 2. Per trip, data from the three sources (i.e., the OBD2 logger and the two cameras) were synchronized. All camera footage was processed manually. All data were recorded at a frequency of 1 Hz.

TABLE I
Measurement Data

Quantity	Unit	Equipment
ACC status	on / off	Camera dashboard
Speed	km/h	OBD2 logger
Acceleration	km/h/s	OBD2 logger
Spacing	category 1–8	Forward-facing camera
Lane	0 = acceleration lane, 1 = right-hand lane, etc.	Forward-facing camera

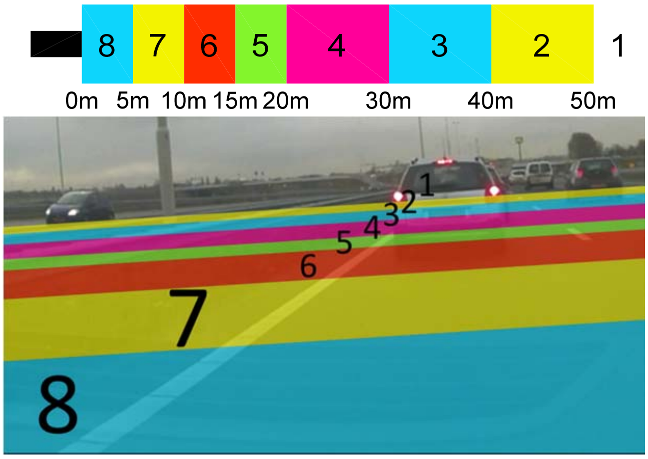

Fig. 2. Top: the eight spacing categories in top-down view. The black rectangle represents the host vehicle. Bottom: The video overlay containing the eight spacing categories.

From the measurement data, we derived lane changes and headway (i.e., the distance between vehicles in seconds). Headway was defined as spacing divided by speed. Headways were only calculated for speeds above 20 km/h. Spacing category 1 (> 50 m) was excluded from the evaluation of spacing and headway.

The traffic state was estimated based on the speed measurement. Specifically, for each speed sample, we calculated a 1-minute average speed ranging from 30 s before to 30 s after the sample. Traffic was categorized in three traffic state categories: free flow traffic (>100 km/h), saturated traffic (60−100 km/h), and congestion (<60 km/h).

C. Participants

For this experiment, 8 drivers with ACC experience volunteered to participate over the course of 4–5 weeks. Their characteristics, including the characteristics of their cars, are shown in Table II. Heterogeneity of the sample was limited as generally the participants were experienced male drivers.

Participants were given a booklet which explained the goal of the study, and which instructed participants to drive as they usually do. Four out of eight drivers were instructed not to use ACC for the final 2 weeks of the experiment, because too little data of driving without ACC would otherwise result (these participants tended to use ACC for more than 50% of their freeway driving). The booklet also presented the equipment, information on privacy and safety, and contained an informed consent form. This has been approved by the Human Research Ethics Committee of Delft University of Technology and all participants provided written informed consent.

TABLE II
PARTICIPANT CHARACTERISTICS

Characteristic	Frequency
Gender	7 (male), 1 (female)
Age	1 (40–49 yr), 6 (50–59 yr), 1 (60+ yr)
Driving experience	1 (10–19 yr), 7 (20+ yr)
Annual km	3 (20–30k), 1 (30–40k), 4 (40+k)
Usage	1 (business), 7 (private + business)
ACC experience	4 (40–600 km/week), 4 (600–800 km/week) 6 (3–6 mo), 1 (6–12 mo), 1 (24+ mo)
Car brand	4 (Volvo), 2 (Peugeot), 1 (Skoda), 1 (BMW)
Transmission	3 (manual), 5 (automatic)
Lower ACC limit	4 (yes), 4 (no)
ACC choice	5 (yes), 2 (yes, in package), 1 (no)
ACC instructions	2 (no), 3 (yes, slightly), 2 (yes), 1 (unknown)
Risk aware	2 (yes, slightly), 6 (yes)
ACC rating (1–10)	6.5; 7; 7; 7.5; 8; 8.5; 9; 9.5

The full questionnaire format can be found in [18].

D. Trip Characteristics

The driving behavior of each participant was recorded for 4–5 weeks, while they were performing their usual trips. In order to obtain a balanced dataset (i.e., ACC On and ACC Off both well represented), not all data were processed. Per participant, at least 6 hours of data were processed, if the participant provided more than 6 hours of data. Trips that were included were chosen such that the amount of ACC On data was between 50% and 75% per participant, if possible.

The resulting duration per participant for different combinations of traffic state and ACC status is given in Table III. For 7 combinations of traffic state, participant and ACC mode, less than 5 minutes of data were gathered. These are indicated in solid grey in Table III. These data were excluded from the analysis unless explicitly stated otherwise. For example, results regarding ACC (and averages of ACC On and ACC Off) in free flow conditions were derived from participants 1–3 and 5–8, because Participant 4 had too little data with ACC Off in free flow. Note that little data (only 58 minutes) were obtained with ACC On in congestion, because

TABLE III
AMOUNT OF PROCESSED DATA PER TRAFFIC STATE AND ACC STATUS [HH:MM:SS]

Traffic state	ACC	Participant								Total
		1	2	3	4	5	6	7	8	
Free	Off	2:38:55	1:38:37	3:37:00	0:02:16	1:11:19	3:23:42	1:18:55	0:43:06	14:33:50
	On	3:57:38	3:37:37	1:06:23	1:56:24	3:19:10	0:53:03	3:24:14	0:45:37	19:00:06
	Total	6:36:33	5:16:14	4:43:23	1:58:40	4:30:29	4:16:45	4:43:09	1:28:43	33:33:56
Saturated	Off	0:21:15	0:30:51	1:06:42	0:02:15	0:32:20	1:11:36	0:34:59	0:18:18	4:38:16
	On	0:38:00	0:16:52	0:11:59	0:33:49	1:07:22	0:27:51	0:59:53	0:24:12	4:39:58
	Total	0:59:15	0:47:43	1:18:41	0:36:04	1:39:42	1:39:27	1:34:52	0:42:30	9:18:14
Congested	Off	0:11:36	0:31:07	0:55:47	0:08:12	0:19:42	0:59:10	0:33:05	0:14:04	3:52:43
	On	0:00:04	0:00:00	0:00:00	0:00:30	0:41:40	0:00:00	0:10:06	0:05:14	0:57:34
	Total	0:11:40	0:31:07	0:55:47	0:08:42	1:01:22	0:59:10	0:43:11	0:19:18	4:50:17
Total	Off	3:11:46	2:40:35	5:39:29	0:12:43	2:03:21	5:34:28	2:26:59	1:15:28	23:04:49
	On	4:35:42	3:54:29	1:18:22	2:30:43	5:08:12	1:20:54	4:34:13	1:15:03	24:37:38
	Total	7:47:28	6:35:04	6:57:51	2:43:26	7:11:33	6:55:22	7:01:12	2:30:31	47:42:27

Solid grey = Excluded because less than 5 min of data. Shaded grey = Excluded because less than 5 min of data for the other condition.

TABLE IV
DIFFERENCES BETWEEN ACC OFF AND ON, AVERAGED OVER DRIVERS (N = 7 FOR FREE AND SATURATED, N =3 FOR CONGESTION)

Quantity	Unit	Traffic state	ACC		Difference			*t*-test
			Off	On	mean	min	max	
Spacing Mean	[m]	free	30.50	35.11	15.1%	5.3%	29.4%	$t(6) = 4.34, p = 0.005$
		saturated	23.11	29.99	29.8%	3.0%	56.6%	$t(6) = 4.49, p = 0.004$
		congestion	12.53	14.39	14.8%	7.1%	26.8%	$t(2) = 5.10, p = 0.036$
Spacing SD	[m]	free	10.24	8.14	-20.4%	-33.3%	-10.6%	$t(6) = -6.99, p < 0.001$
		saturated	9.41	7.53	-20.0%	-49.6%	-1.9%	$t(6) = -2.82, p = 0.030$
		congestion	8.49	7.62	-10.2%	-31.0%	5.6%	$t(2) = -1.10, p = 0.388$
Headway Mean	[s]	free	0.99	1.15	16.5%	6.7%	31.0%	$t(6) = 5.00, p = 0.002$
		saturated	0.98	1.20	22.8%	-6.1%	42.4%	$t(6) = 3.44, p = 0.014$
		congestion	1.42	1.64	15.3%	8.5%	24.2%	$t(2) = 2.09, p = 0.172$
Headway SD	[s]	free	0.32	0.26	-18.6%	-35.8%	-6.2%	$t(6) = -4.28, p = 0.005$
		saturated	0.40	0.30	-24.1%	-55.4%	-7.3%	$t(6) = -3.35, p = 0.015$
		congestion	0.75	0.80	6.5%	-16.3%	35.3%	$t(2) = 0.44, p = 0.706$
Acceleration SD	[m/s^2]	free	0.26	0.22	-13.1%	-20.1%	-1.0%	$t(6) = -5.09, p = 0.002$
		saturated	0.49	0.34	-31.5%	-50.4%	-2.3%	$t(6) = -4.89, p = 0.003$
		congestion	0.68	0.65	-4.5%	-29.9%	26.8%	$t(2) = -0.23, p = 0.836$
Lane Mean (1 = right)	[#]	free	2.06	2.01	-5.0%	-69.8%	77.9%	$t(6) = -0.30, p = 0.778$
		saturated	1.86	1.76	-9.1%	-49.2%	19.6%	$t(6) = -1.03, p = 0.343$
		congestion	1.98	2.13	14.9%	-59.4%	77.8%	$t(2) = 0.37, p = 0.745$
Lane changes	[#/h]	free	77.34	62.38	-19.3%	-40.7%	6.8%	$t(6) = -2.29, p = 0.062$
		saturated	66.70	42.47	-36.3%	-58.1%	14.3%	$t(5) = -2.06, p = 0.094$
		congestion	-	-	-	-	-	-

participants tended to disable their ACC in congestion and/or because ACC does not operate in low speed conditions. Most trips were during regular daytime and on workdays.

III. RESULTS

Averages and standard deviations across drivers were calculated for driving characteristics related to traffic flow (Table IV). The percentage differences between the averages for ACC On and ACC Off are also shown, as well as the minimum and maximum difference among the 8 participants. The minimum and maximum difference can be used to infer whether the mean difference is consistent for all participants. For example, if all differences have a positive or negative sign, the percentage difference is consistent for all participants. Finally, results of a paired *t*-test between ACC Off and ACC On are included.

Both spacing (distance) and headway (time) show a similar pattern, where ACC On shows increased spacing and headway relative to ACC Off. Standard deviations of spacing and headway are generally lower for ACC On. However, in congestion, the change in standard deviation of headway shows a mixed pattern among the participants.

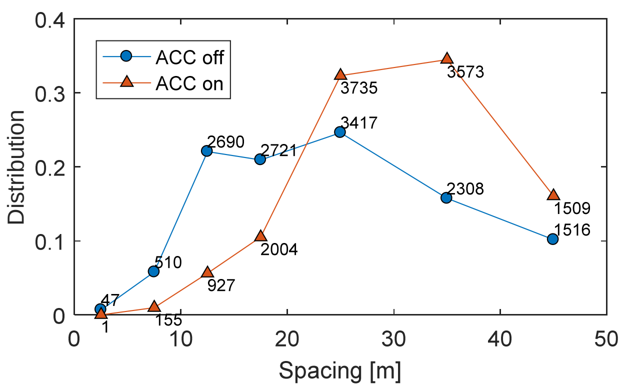

Fig. 3. Distribution of spacing for ACC Off and ACC On in saturated conditions. Distributions were determined per driver and then averaged (N = 7). The numbers indicate the number of 1-second measurements.

Accelerations show a smaller standard deviation with ACC On in free flow than in saturated conditions. For congestion, again a mixed pattern exists, with some drivers showing an increase of the standard deviation of acceleration and others showing a decrease. The average lane number hardly changes on average, but a mixed pattern is visible in all traffic states whereby some drivers are more likely to stick on the right lane, and others are more likely to stick on the left lane. Finally, for most drivers, the number of lane changes is lower for ACC On compared to ACC Off.

It should be noted that, except for mean spacing, none of the differences between ACC Off and ACC On found in *congestion* are statistically significant at a 5% significance level. This is probably due to the small number of participants who drove in congestion with ACC On. The same holds for the mean lane and the number of lane changes in all traffic states. It is interesting to note that although the mean is not statistically significant for these characteristics, the minimum and maximum change of the 8 participants show a mixed pattern with a strongly negative minimum and a strongly positive maximum, suggesting that traffic flow is affected.

The increased spacing and headways are especially found in saturated conditions (increases of 29.8% and 22.8%, respectively). Fig. 3 shows the distribution of spacing in saturated conditions. With ACC On, the probability of spacing below 20 m is considerably reduced in saturated conditions relative to ACC Off. A previous naturalistic driving study also found that in heavy freeway traffic, prevalence of headways shorter than 1 second reduced by one third [10].

In order to examine the dynamic properties of both ACC On and ACC Off, average headway and spacing have been derived for different acceleration values. Because the data were logged at 1 Hz, and because speed measurements were available as rounded integer values in km/h, acceleration values were available in 1 (km/h)/s increments. We have aggregated the traffic states ‘saturation’ and ‘congestion’ for

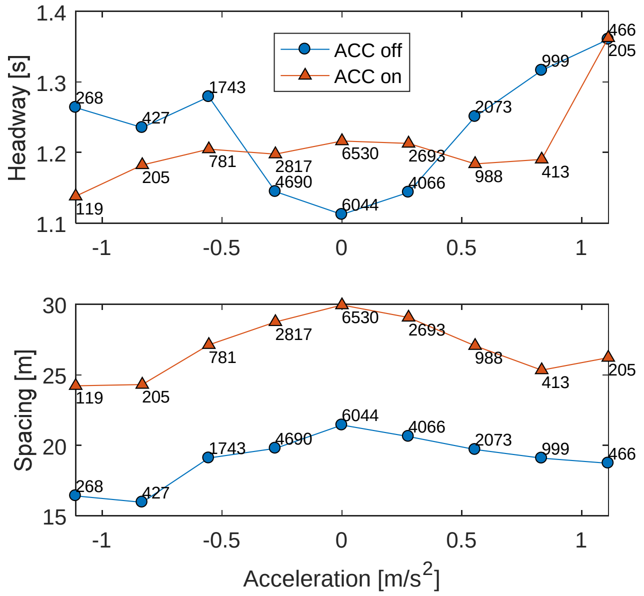

Fig. 4. Dynamic relation between headway, spacing (excluding spacing for speeds below 20 km/h), and acceleration in saturated and congested conditions. Headway and spacing were determined per driver and then averaged (N = 8). The numbers indicate the number of 1-second measurements.

this analysis and included all participants. As we aggregate ‘saturation’ and ‘congestion’ each driver supplied over half an hour of data for this analysis. Participant 3 supplied the least data per state, being 272 s for ACC On after excluding spacing that is out of range (Category 1). We left out data where the combined duration of ACC On and Off was less than 5 minutes over all drivers for a given acceleration value. Spacing measurements for speeds below 20 km/h have been excluded for an unbiased comparison with headways (which were not calculated for these speeds). The resulting evaluated range with sufficient data is from -1.11 m/s^2 to 1.11 m/s^2. Fig. 4 shows the average headway and spacing values averaged over all participants. Three regions can be distinguished:

- *Deceleration* ($v' < -0.5$ m/s^2). ACC On had a larger spacing but smaller headway compared to ACC Off; thus the speed is higher for ACC On. The relatively low headway for ACC On can be explained by the fact that, in order to decelerate, ACC requires ‘incentive’ in the form of a small headway. Conversely, drivers with ACC Off decelerate in a more ‘relaxed’ fashion by adopting a large headway with respect to the vehicle in front.
- *Stationary* (-0.5 $m/s^2 < v' < 0.5$ m/s^2). In this acceleration range, traffic is more or less in equilibrium. It can be seen that with ACC On, a larger headway and spacing are maintained than with ACC Off.
- *Acceleration* (0.5 $m/s^2 < v'$). ACC On had a larger spacing but smaller headway than ACC Off, which implies that the speed is higher for ACC On. It appears that ACC sticks to the predecessor during acceleration. Again, drivers with ACC Off behave in a more relaxed fashion by leaving a relatively large headway during acceleration.

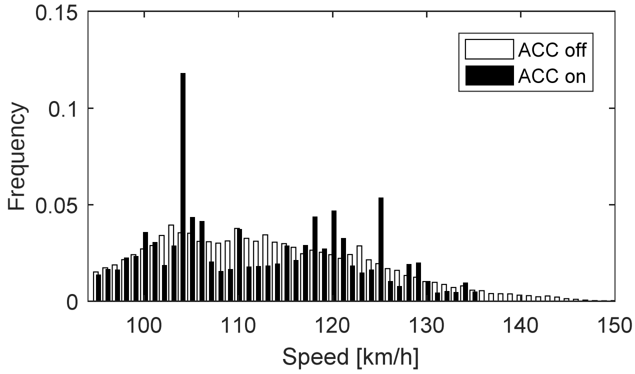

Fig. 5. Distribution of driving speed.

Finally, we assessed the distribution of driving speed. In Fig. 5, it can be seen that distinct peaks exist in the speed distribution for ACC On. These are common speed limits in the Netherlands (i.e., 100 km/h & 120 km/h) or at a margin of 4–5 km/h above the limit, where no fines are issued. One more peak is found at 118 km/h, which also seems correlated with the speed limit of 120 km/h.

IV. Discussion

The naturalistic driving study presented in this paper shows that with ACC enabled, average headways are larger while the standard deviations of spacing, headway, and acceleration are smaller. This suggests a deterioration of capacity and travel time, but also more stable traffic. The probability of spacing below 20 m in saturated conditions is considerably reduced, which suggests better safety. This confirms findings in the literature [3], [10], [15], [16], [17].

The smaller standard deviation of accelerations in free flow can be explained by the fact that ACC is able to maintain a speed more accurately than a driver does. From the reduced standard deviations, we may conclude that ACC is less likely to induce disturbances in free flow or saturated conditions that may cause breakdown to congestion, than driving with ACC disabled. It can however not be concluded whether ACC responds in a more stable manner in dynamic traffic situations (i.e., whether disturbances in traffic are enlarged to a greater or lesser extent with ACC On compared to ACC Off).

Our investigation of the dynamic relation between headway, spacing, and acceleration provides insight into the response of drivers with ACC Off or with ACC On. For accelerations between -0.5 m/s^2 and 0.5 m/s^2 with ACC On larger headways result than with ACC Off. Most data have been gathered in this range, which is consistent with the general conclusion based on average values.

For accelerations below -0.5 m/s^2, headways are smaller with ACC On than with ACC Off. When decelerating, ACC seems to require a smaller actual headway and a larger set (or desired) headway to obtain the same level of deceleration as a driver with ACC Off. This suggests that ACC has an important limitation with respect to human driving, which is anticipation of traffic ahead.

In the range of accelerations above 0.5 m/s^2, headways are also smaller with ACC On than with ACC Off. This suggests that ACC requires less incentive to reach the same level of acceleration as drivers with ACC Off. Given the mechanical nature of ACC, the cause of this difference with situations of deceleration probably lies in human factors: Drivers are known to increase their headway in congestion [11], and overall the resulting response to an accelerating predecessor is not as timely as with ACC On. Drivers who are not using ACC are apparently unable or unwilling to anticipate during acceleration. This makes sense from a safety point of view, as anticipation is not required for safety during acceleration. That is, when leading vehicles accelerate, a collision is not imminent. In summary, the results indicate that ACC is able to increase queue discharge rate, which is positive regarding travel time delay.

Given that individual drivers show considerable changes in their preferred lane between ACC Off versus ACC On, it seems that two behaviors may occur regarding lane changing. When enabling ACC, the driver either stays in a slower lane and lets the ACC follow the predecessor, or the driver decides to stay in a faster lane. A reason for the latter could be that the driver wants to avoid the response of their ACC that occurs when changing to another lane (and possibly change back some time later). The average lane number, however, is hardly affected by ACC, and the difference is not statistically significant. In saturated conditions, a reduction of 36% in the number of lane changes results, which is a considerable difference given the fact that lane changes may trigger traffic flow breakdown [19]. However, this too is not statistically significant.

With ACC enabled, drivers often set their ACC speed at a specific value in relation to the speed limit. The resulting speed distribution shows peaks that, for large penetration rates of ACC, might create side effects. For example, in speed-enforced 80 km/h zones, traffic across lanes shows similar speeds affecting lane distribution and traffic breakdown in a negative manner [20]. Excessive speeding is less with ACC.

In conclusion, this naturalistic driving study shows that ACC increases headways, likely resulting from an otherwise insufficient level of deceleration when approaching slower traffic. On the other hand, traffic was found to be more stable, as indicated by the spacing, headway, speed, and acceleration all having smaller standard deviations for ACC On compared to ACC Of. Finally, the results suggest that ACC increases queue discharge rate. It should be noted that our study collected relatively little data in congestion (3 drivers with sufficient data). Future research will aim at investigating the impacts on traffic flow characteristics by the empirically found changes in driving characteristics through simulation. Furthermore, future research could adopt a more controlled approach with a larger number of participants where one group of drivers is instructed not to use ACC and another group is instructed to use ACC.

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