Effects of ACC and FCW on speed, fuel consumption, and driving safety

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Abstract— **Intelligent Transportation Systems (ITS) are widely expected to deliver a major contribution to the improvement of driving comfort as well as road safety. An insight into the benefits of ITS is an important ingredient in the deployment of ITS. Assessing these benefits is one of the research goals within the 7th Framework Program of the European Commission. Field** Operational Tests (FOT) have emerged as an important research methodology for assessing the impact of ITS on driver behavior and performance, traffic safety, traffic efficiency as well as the environment. **Within the euroFOT project, a large scale field test that involves approximately 1000 instrumented vehicles on the road all over Europe the impact of eight selected ITS function is tested. Most of these vehicles have one or more ITS applications on board, including continuously operating ones like Adaptive Cruise Control (ACC) and Forward Collision Warning (FCW). This paper describes the method applied for the FOT to assess the impact of the ACC and FCW. The euroFOT approach has some similarities to existing FOTs but includes novel aspects to handle specific limitations and conditions of the FOT and the available data. The paper further describes the final results of the data analysis based on the predefined hypotheses to answer the research questions of the project.**

Keywords-Transportation, Intelligent Transportation Systems, Driver Behavior, Driver Assistance Systems, Field Operational Tests, Data Analysis

I. INTRODUCTION

Today road transport in Europe faces enormous challenges caused by economical and social changes in the last years. These lead to new demands for each individual as well as for the entire economy. The individual demand for personal mobility and flexibility is increasing in Europe as it has already been over the last ten years. Studies show that the number of vehicles has grown from around 400 vehicles per 1000 inhabitants in 1995 to 480 in 2005 within the EU25, which caused a higher traffic density [1].

This growing number of vehicles is accompanied by an increased driver workload, due to increased traffic complexity and driving tasks. This development results in a higher accident risk. In order to support drivers and to make driving safer as well as more comfortable and efficient with respect to environment and traffic flow advanced driver assistance systems have been developed. Their potential to provide a positive impact on traffic safety and efficiency is well recognized [2].

Over the past years Anti-lock Braking Systems (ABS) or the Electronic Stability Program (ESP) as well as passive safety systems, e.g. safety belt or airbag, caused a significant reduction of accidents with injuries and especially of traffic fatalities. However, there are still 35000 fatalities on European roads every year. Hence, the European Commission (EC) has announced in the 2010 White Paper on transport the objective of halving the number of fatalities on European roads until 2020 [3]. To meet the objectives a wider introduction of ITS is targeted.

Besides other test methods, such as tests in simulators and driving tests on a test track, field operational test are recognized as a reliable method to test the short as well as long term effect of ITS in real driving conditions. Within a FOT vehicles equipped with ITS functions are driven by a representative sample of drivers under normal driving conditions in real traffic [4].

A. *State of the Art*

Previous FOTs have been identified as an important method of verifying the real-world impacts of ITS. In the United States (US) large scale FOTs have already been introduced in 1996 [5] as an evaluation method for ITS with the aim of proving that such systems have an impact on driver behavior and road safety [6], [7], [8]. In the following table an overview of conducted FOTs is presented.

TABLE I. OVERVIEW PREVIOUS CONDUCTED FOTS IN THE US AND EUROPE

	FOT	Tested Systems	Number of vehicles	Number of participants	Duration of FOT [Month]	Mileage [km]
USA	NHTSA ICC FOT (1996 – 1998)	ICC	10	108	13	108.000
	VOLVO IVI FOT (2001 – 2004)	ACC, CWS, AdvBS	100	> 1000	> 24	16.300.000
	ACAS FOT (2003 - 2004)	ACC, FCW	14	66	9	158.000
	Mack IVI FOT (2004 – 2005)	LDW	22	31	12	1.400.000
	IVBSS FOT (2008 – 2010)	FCW, LDW, CSW, LCM	26	108	10	1.394.000
Europe	ISA Sweden (1999 – 2002)	ISA	5000	ca. 10.000	ca. 12	75.000.000
	The Assisted Driver (2006 - 2007)	ACC, LDW	20	20	5	n.a.
	SeMiFOT (2008 - 2009)	ACC, FCW, LDW, BLIS,	14	39	6	171.440
	euroFOT (2008 - 2012)	ACC, CSW, FCW, LDW, SRS, BLIS, FEA, IW	1000	1000	12	34.000.000

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

Within these FOTs several ITS functionalities have been evaluated. In 2011 the IVBSS FOT provided valuable information with respect to the benefit of crash warning systems [9]. In Europe FOTs have been conducted on a national or regional level, particularly on intelligent speed adaptation systems (ISA) (see [10] and [11]) and LDW systems [12] in the beginning. Within the 7th framework program of the EC two large scale FOTs have been started in 2008 on European level. The TeleFOT project [13] is focused on the evaluation of nomadic devices whereas the euroFOT project [14] is focused on the evaluation of eight ITS functionalities.

Main difference between the US and European FOTs is the development status of the tested ITS. In the US the development of the ITS function is conducted within the preparation phase of the FOT while in the most national FOTs within Europe only series products with already integrated vehicle sensors have been tested.

B. *German1-Vehicle Management Center (VMC)*

For the first time series market ITS products are tested within a large scale FOT with a representative sample of drivers as part of their normal driving routine in Europe. By means of instrumented vehicles data has been collected and evaluated within the field operational test, in order to answer the pre-defined research questions. It has established a comprehensive, technical and socio/economic assessment program for evaluating the impact of ITS on safety, traffic efficiency, environment and user-acceptance in real life situations. The fleet of the euroFOT project has been coordinated by five Vehicle Management Centers (VMC) (France, Germany (two test sites), Italy and Sweden) across several European countries.

This paper focuses on the experimental approach and the data analysis at the German1-VMC. A fleet of 200 vehicles is managed, which consists of 60 trucks from MAN, 100 passenger cars from Ford and 40 passenger cars from VW. The field operational test is conducted for a period of twelve months. The tested ITS functions cover Adaptive Cruise Control (ACC), Lane Departure Warning (LDW), Forward Collision Warning (FCW) [15]. The following figure provides an overview of the German1-VMC.

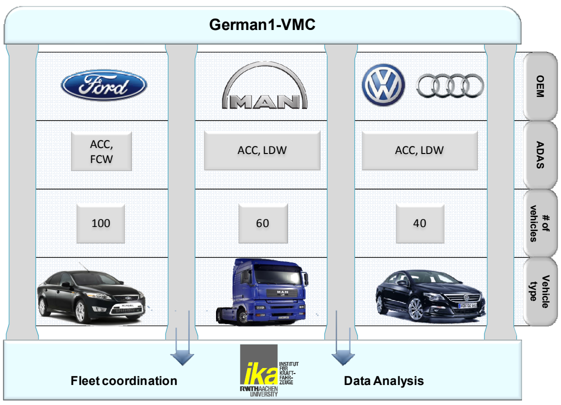

Figure 1. Tested ITS functions and fleet com-position at the German1-VMC

All 200 vehicles are equipped with Data Acquisition Systems (DAS), which allow recording and temporary storage of all relevant measured values (vehicle speed, acceleration, time-headway, steering angle etc.) as well as the transfer of previously recorded data to a central storage server. Objective data have been recorded from the vehicle CAN bus (Control Area Network) at high frequency (10 Hz) for an extended period varying from six months to one year. Subjective data have been recorded in questionnaires.

As a result of this huge amount of data a detailed analysis of the complete data within the planned period of time is not feasible. Hence, a limitation of the evaluation to relevant driving events is necessary, in which the particular tested functions have an influence (e.g. car following, lane change manoeuvres, critical distance situations). These events are extracted from the collected data by an automated process which has been developed at the Institut für Kraftfahrzeuge (ika). The event recognition algorithm automatically detects certain patterns (combinations of different measures) in the CAN- and GPS-data. Although this approach demands high computational performance, it enables saving considerable amounts of time compared to manual processing of the large amount of data. In the following the methodology, the data processing chain as well as the automated event recognition processes are presented.

II. METHODOLOGY

The relevant data to be collected within the field test has been derived from the research questions of the project. Based on these research questions (assessment of the impact of ITS on traffic safety, traffic efficiency, environment as well as driver behavior and acceptance) hypotheses to be tested (e.g. ACC decreases the number of incidents) have been defined. By means of the hypotheses the required signals and data sources have been identified. The definition process applied for the euroFOT project is presented in Figure 2.

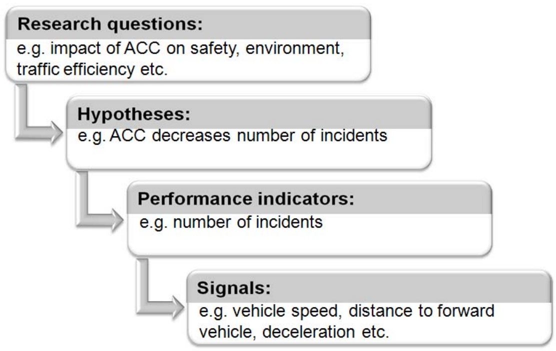

Figure 2. Definition process of required signals

For each operation site an adapted experimental design has been defined, in order to consider the specific basic conditions. In general, the experimental design consists of a baseline (system-off period) as well as a treatment period (system-on period). At the German1-VMC the first three months of the field operational test serve as a baseline period during which the ITS functions are deactivated, while data on driving performance (e.g. vehicle speed, acceleration etc.) is collected.

During the following treatment period, the functions to be tested are activated and the recording of the same driving data is continued. Comparisons between recorded driving behavior and performance data for the same participant in the treatment and baseline periods are made, in order to assess the impact of the functions. As an example the figure below presents the experimental design for 100 passenger cars at the German1-VMC.

Ford	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
100 passenger cars (ACC + FCW)	Baseline phase (A) (-)			Treatment phase (B) (ACC + FCW)								

Figure 3. Experimental design for the fleet of 100 passenger cars at Ford

The passenger cars are equipped with ACC and FCW. After the three month baseline period (A) the functions are activated and can be used by drivers as they usually would do. No further instructions are given to the drivers. The drivers are free to use the functions where and when they like [16]. By means of comparisons between relevant data sets for the same participants in the baseline phase (A) and treatment phase (B) the impact of the tested functions (ACC and FCW) is assessed. To ensure that the comparison is conducted under the same conditions in baseline and treatment so called situational variables (weather, road type, lighting condition etc.) are considered.

During the whole experimental phase data is collected from the instrumented vehicles. For the German1-VMC it has been decided to continuously record the required signals with defined sampling rates instead of collecting data only after detection of a relevant situation. The relevant situations (e.g. incident situations) are detected afterwards offline at the server. Thereby some remarkable disadvantages can be avoided. One of the main disadvantages of a discontinuous recording of the data is a loss of possibly relevant data because of not well-suited event recognition (e.g. wrong thresholds). The detection cannot be adapted at a later stage, if relevant raw data has not been collected. The availability of the complete raw data (continuously record) allows reprocessing of information after implementing any desired adaptations. However, the high amount of data that is generated compared to the situation-based approach results in higher demands on the data management.

A. Data management

For data collection in the field, the German1-VMC has equipped in total 200 customer vehicles (owned by participants) with data acquisition systems (DAS). These DAS collect data from up to four CAN busses of the vehicles and additionally GPS information. Other signal sources on vehicle side are not used at the German1-VMC, in order to ease the integration (no modification of customer vehicles) of the DAS into the vehicles compared to other scenarios such as integration of additional sensor equipment (e.g. video sensors).

The data measured on the connected CAN channels are stored in a first stage on a flash storage device installed on the DAS. The DAS at the German1-VMC offers the possibility to communicate with the device during operational time of the field test using an integrated GPRS module. This allows wireless uploading of recorded information to a centralized server system, while the DAS is simultaneously collecting data. Therefore, the data is compressed and encrypted. By means of the GPRS connection the DAS status and operation on board of the vehicle can also be checked and monitored during the entire operation time.

After the data has been uploaded to the server, further processing steps are conducted. Within these steps the data are enriched with additional attributes from a digital map (e.g. road type, speed limit), which are derived by means of GPS information. Afterwards, all necessary signals for the detection of relevant events and situational variables are available. Finally the processed data as well as the initially recorded data is stored on a server. Here the raw data is stored in files on a per-trip basis as a backup for the case that a re-processing of certain data sets will be necessary. The processed data is filled in tables of an SQL-server. Data on the SQL-server serve as basis for the evaluation.

The upload procedures are designed and implemented to work fully autonomously. Autonomous operation means that no user interaction – neither on the driver side nor on the operator side – is required. Hence, the drivers are totally kept out of the data retrieval loop. No training of the participating drivers is needed and the loss of data due to maloperation is excluded [17].

B. Data processing

All data files collected by the DAS are on a trip basis. This means that the recording is started as soon as the vehicle's engine is started and is completed at the latest one hour after the vehicle's engine has been switched off. The follow-up time is applied, in order to provide additional time for data upload, which might have been not possible during the trip. If all collected data has been uploaded to the server during the trip, the DAS will be deactivated directly after the engine has been switched off.

The pre-processing (data quality check, data enrichment etc.) is designed to work on a per-trip basis, while the post-processing (on SQL-database) builds a more complete overview. Within the data quality analysis checks for missing data and checks for signal ranges are considered together with wrong dynamic behavior and incoherent behavior of signals. The data quality checks are performed directly after the upload and after each modification of the data.

In the next processing step the available signals are used to detect relevant events (e.g. incidents, hard braking) as well as situational variables (weather conditions, road type etc.), in order to classify the data for focusing the analysis on relevant data sets. Furthermore, the performance indicators (PI) needed for testing of the hypotheses (e.g. time-headway, time to collision) are calculated. For the whole process additional information is needed, which is derived from the existing signals (GPS and vehicle dynamics) by using attributes from digital maps (e.g. road type, number of lanes etc.). These processes are conducted by the Event, Enrichment and PI Manager. Each function (event recognition, PI calculation etc.) is realized as a separate extension of this software element [18].

III. RESULTS

The following results examine different aspects of the common ACC and FCW use by non-professional drivers, based on the data collected for 100 passenger cars at Ford. Those aspects are the influence of the system use to the longitudinal driving behavior and safety. In addition, the ACC usage is evaluated. Within these evaluations it is not possible to assess traffic flow effects that results from the interaction between equipped and unequipped vehicles. To test possible benefits of higher ACC penetration rates within a vehicle fleet simulation of different traffic flow scenarios were conducted.

More than 1.3 million km of data driven by 84 drivers was used for the statistical analysis of the effects of the ACC system. All of these considered drivers fulfilled the predefined requirements concerning the distribution of mileage over the three experimental phases (baseline, treatment overall and treatment system active). In the following "treatment" describes phases in which the ACC is active.

The statistical analyses were done as repeated measures analyses of variance (ANOVA) with factors 1-3 above plus experimental phase or as Wilcoxon test for non-Gaussian distributed data. In the tables for the results the survey sample size (N), probability (p) and the variance ratio between explained/unexplained (F) are shown. Results were considered to be significant for $p < 0.05$. The shown percentage changes are change in median values because the data is not Gaussian distributed.

The data gathered within the FOT was filtered by the four following criteria:

1) Travel time per trip > 5 min.
2) Vehicle speed > 50 km/h
3) Road type = Motorway (only ACC evaluation)
4) Time-headway (THW) > 0 sec (only ACC evaluation)

Only trips with a travel time higher than five minutes were considered to exclude a high number of short trips where the benefit of system activation is assumed to be very small. The second criterion was chosen to avoid driving in congestion and intersections or roundabouts. For the ACC evaluation the analysis focused on driving on motorways (criterion 3) and in car following situations (criterion 4), where the highest benefit of ACC is expected.

A. Driving behavior

The handover of the longitudinal vehicle control to the ACC system has various effects on the driving style. Two of these effects are the influence on the average speed and the fuel consumption. Both are related to a different acceleration behavior between the ACC system and the vehicle driver. The predefined hypotheses assume that the average speed as well as the fuel consumption decrease in phases where the ACC system is active.

Comparing baseline and treatment a significant reduction in the average fuel consumption of 4.9% was found (see Table II). The significance for this effect is higher than 99.99%. In addition, the fuel consumption was investigated for the situational variables *weather* (good (dry) and bad (rain) condition) and *lighting (daytime and night condition)*. All conditions show the significant influence of the ACC state on the fuel consumption ($p = 0.024$ for *weather* and $p = 0.0002$ for *lighting*) but no influence of the situational variables to the ACC related change in fuel consumption. Due to the fact that not all participants of the FOT had a sufficient amount of mileage within the conditions specified by the situational variables and the ACC state the survey sample size for the *weather* and *lighting conditions* reduces to N = 54.

The reasons for the reduction in fuel consumption might be related to a more homogenous speed distribution with less (and less strong) accelerations when driving with the system.

As a second parameter of the driving behavior the average speed is analyzed. Contrary to the hypothesis, that the average speed will decrease using the ACC system, an increase of just less than 1% was found within the treatment data (see Table II). Since the analysis of the average speed for the situational variables *weather* and *lighting conditions* show opposite effects between -0.9% and 1.3% it is not possible to give a clear answer to the hypothesis even though the ANOVA indicates a change within the significance limits ($p=0.009$) for the overall evaluation.

TABLE II. EFFECTS OF ACC USE ON DRIVING BEHAVIOR

Effect on driving behavior	Percentage change	N	p	F
Fuel consumption	-4.9%	84	< 0.0001	17.32
Average speed	0.96%	84	0.009	7.139

B. Driving safety

The combined ACC+FCW system is expected to have an high influence on the driving safety by maintaining a safe distance to the vehicle driving ahead and warning the driver against possible collisions because of e.g. distraction. Two indicators for increased driving safety were considered in the testing of the related hypotheses: Time-headway (THW) and the number of critical situations.

Safety benefits due to changes in distance during car following situation are evaluated with the help of the measured CAN data on THW. The hypotheses on THW do not only consider a change in the average THW, but also the proportion of THW under 0.5 seconds which represents critical distances to other vehicles.

Both indicators show improvements for driving safety in the analysis. The average THW is increased by 12.5% in the overall assessment and between 7% (weather) and 14.6% (lighting) in the evaluation with consideration of the situational variables. All of these changes are significant with p-values smaller than 0.0001 (compare Table III). The percentage of THW values below 0.5 seconds shows a reduction of 82.7% between baseline and treatment. To consider the highly non-Gaussian distribution of the appearance of THW < 0.5 events the statistical analysis was done with a Wilcoxon test. Like for the average THW all conditions are highly significant ($p<0.0001$).

The increase in average THW and the high reduction of THW < 0.5 events are obviously related to the design of the ACC system. It is not possible to set time-headways under 1.2 seconds. Therefore, those events can only result from cut-in maneuvers or strong decelerations of the vehicle driving ahead. Also the average THW is influenced by the discrete settings for the time-headway.

TABLE III. EFFECTS OF ACC USE ON DRIVING SAFETY

Effect on safety indicators	Percentage change	N	p	F
Average THW	12.5%	84	< 0.0001	16.691
Proportion THW < 0.5 sec	-82.7%	84	< 0.0001	-7.858
Incidents	-72%	84	< 0.0001	-5.836
Hard brakings	-40.1%	84	< 0.001	-3.561

The second measure for driving safety is the number of critical situations. This indicator is split into the evaluation of incidents and the number of hard brakings. A detailed description of the detection of incidents developed at ika is provided in [19]. Hard brakings [19].are counted when the braking force exceeds a speed depending threshold

Like the change in THW < 0.5 events the percentage of incidents and hard braking is significantly lower within the treatment phase. 72% less incidents and 40.1% less hard braking maneuvers were recorded during the system activation. Significant results could also be stated in the different weather and lighting conditions where the reductions varied between 74.2% and 100% for the incidents and 45.1% and 49.7% for the hard brakings.

In general, the data analysis shows a high benefit of the use of the ACC+FCW system with regard to the driving safety. The influence of the single safety indicators to the absolute number of crashes is difficult to determine (for more information see [20]) but the results indicate a high potential. In Figure 4 the results for the driving safety indicators are summarized.

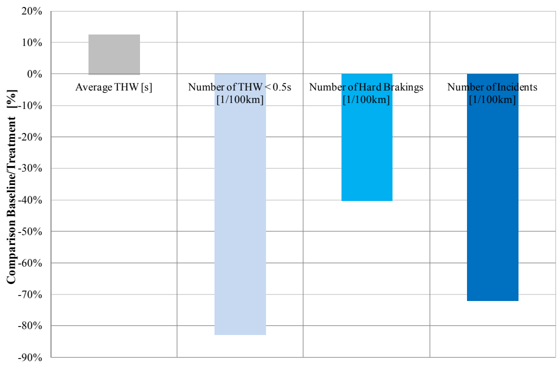

Figure 4. Comparison of safety indicators between baseline and treatment phase

C. *Usage*

The system usage was assessed by analyzing the percentage of travel time with activated ACC and the number of activations per hour within predefined time periods. Hence, the analysis does not compare baseline to treatment data but subdivides the treatments into nine (months) segments. Due to the fact that not all drivers fulfilled the requirements regarding mileage in the evaluation period the survey sample size is lower (N = 51) than for the previously presented assessment.

Comparing the first and last month of the treatment period the percentage of travel time with active ACC is increased by 35%. The significance of this result (p = 0.016) is shown by a non-parametrical Friedman test with one-way repeated measures analysis of variance by ranks. Also the number of ACC activations per hour increased significantly (p = 0.047 in Friedman test and p = 0.016 in Wilcoxon test) by more than 30% in the last month of treatment compared to first month of treatment.

TABLE IV. ACC USAGE

Effect on usage indicators	Change between first and last month	N	p
Travel time with active ACC	35%	51	0.016
ACC activations per hour	30%	51	0.047

IV. CONCLUSION

The analysis of the FOT data with regard to the benefit of using ACC and FCW shows very positive results. Especially the high potential of such a system to increase the driving safety by reducing the number of critical situations was proofed. Even though a direct transfer to a possible reduction of severe or fatal accidents is not possible the chosen parameters indicate a high benefit.

Nevertheless, there are still factors that influence on the results that are hard to eliminate. The results may e.g. be influenced by the drivers' choice when to use the system or shifts in conditions in which the data is recorded. Therefore, the analysis should be deepened within a follow-up project by focusing on efforts to exclude factors that influence the comparability between baseline and treatment data.

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