The Impact of Electronic Coupled Heavy Trucks on Traffic Flow

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Abstract Over the past decades goods transportation has been increasing and currently widely accepted forecast studies predict a continuation of this trend and a further growth for the coming decades. In order to cope with this growing demand, a better use of existing infrastructure is needed. In order to achieve this optimisation of infrastructure use, intelligent transportation systems and telematics are considered of central importance, by political organisations as well as by freight forwarders and drivers. Current research activity is focusing on the driving assistance system Cooperative Adaptive Cruise Control (CACC) by projects like KONVOI, SARTRE and PATH. The CACC-systems enables the coupling of several vehicles to build a platoon. While the first vehicle of such a platoon is driven manually, the following vehicles operate fully automated, controlled by the CACC system. The technology is developed for long haulage trucks and was successfully tested on the road by the RWTH Aachen, Germany, already.

Furthermore, simulations of trucks and cars equipped with CACC demonstrated positive effects in the form of a harmonisation of the general traffic flow and a reduction of travelling time for the individual vehicle. So far though, it is not known which effects CACC has on the traffic flow and the travelling time if only long haulage trucks are equipped with CACC within a fleet. This research is contributing to closing this gap by simulating the scenario within VISSIM. The results confirm an impact of CACC on the capacity of motorways of up to 5.5 % and up to 6.4 % in travel time of cars, even if only long haulage trucks are equipped with CACC. Therefore it can be stated, that a better use of the existing infrastructure is possible.

Keywords: Cooperative Adaptive Cruise Control; CACC; Intelligent Transportation System; Advanced Driving Assistance System; ADAS; Impact of ITS

1. Introduction

According to prognoses goods transportation on the road will increase during the next decades. Due to this and the current situation, that the infrastructure in many parts already reached its limits, new solutions need to be found. A simple reconstruction or upgrading of the infrastructure won’t be enough. The intelligent transport system seems to be the future although its power spectrum is still under scientific and industrial research and further development. While in the last decades mainly standalone applications have been developed, for the future the communicative application like Car2Car and Car2Infrastructure are prepared. This study will focus the impact of CACC deployed in heavy truck operations.

One of the important developments in the field of the advanced driver assistance system is the Cooperative Adaptive Cruise Control (CACC), where up to seven Trucks, except the leading vehicle, drive fully automatically in a short distance. Additionally the vehicles communicate with each other, so that the reaction from the first to the last vehicle in the Platoon is simultaneously- like a train on road. It is suggested, that the vehicles will drive in a distance of 10m, just on motorway with 2 or more lanes the direction and out of the dangerous zones like bridges, tunnels, construction sites and gateways ([10; 7]).

The existing research is not sufficient to provide discrete data for the modern CACC system, with different truck-portions in traffic flow and different rates of CACC-equipped trucks. Based on an overview of the recent research projects of the impact of CACC, the paper aims to add new results in this research field: the impact of electronic coupled heavy trucks on traffic flow. The used methodology is described in detail and finally the results for the roads capacity and passenger cars speed are presented and discussed.

2. Research of the Impact of CACC on Traffic Flow so far

In the following the existing research projects of the impact of CACC on traffic flow till today will be described in detail and reflected.

In the Chauffeur II project, a very early investigation of the effects of coupled trucks, the effects of the so called Chauffeur-Assistant were identified in simulations. The simulation was performed with VISSIM models (modelling of traffic flow) and FARSI (behaviour of the equipped trucks). The section was 2.5 km long. There were scenarios with two and three lanes and gradients of 0, 2 and 4 percent were implemented. The truck share in the traffic flow was 20 percent. Of these trucks were 10, 20 and 40 percent respectively, with the CA system equipped. Preliminary studies of the project already determined that the CA with low traffic volume has small positive effect on the capacity. In the scenario with 40 percent of equipped trucks, three-lane track and zero percent slope, the highest capacity increase determined was 3.65 percent. Overall the capacity on three-lane motorways with low truck share increases with the use of CA systems [2].

In the context of the German EFAS (Einsatzszenarien für Fahrerassistenzszsteme im Güterverkehr) project various scenarios concerning the organizational forms were implemented. First the driving of coupled trucks in mixed traffic and second, driving on a separate lane which is dedicated to CACC equipped trucks were considered in the scenarios. The scenarios also differ in the number of lanes (two and tree), the truck share (10 and 30 percent), the CACC-penetration rate (10, 20, 40 and 100 percent) and the vehicle density (75 and 90 percent). In the simulations the search, rapprochement and docking process have been integrated. Thus, the vehicles are not coupled per se; the coupling process is part of the simulation. The simulation shows for equipment shares of 10 to 40 percent there are just little or no significant effects on travel speed or capacity. This is because a rapid formation of large convoy organization and associations cannot be assumed, not even at a 100 percent scenario. The effects of CACC can be summarized in the following very interesting results. In the scenario with two lanes, the effects of the CACC were overcompensated by the coupling process of the platoons. For the scenario with three lanes a different outcome was determined. The third lane reduces the impact on surrounding traffic significantly. Platoons of up to five trucks could form and the number of convoy vehicles involved was increased through the available road space. Therefore the cruising speed increases 14 percent and a stabilized flow of traffic was the result. The third scenario included in addition to three lanes for vehicles which are not equipped, an additional one for the CACC-equipped trucks. On this additional lane the total average travel speed could be increased by 20 percent [8].

To investigate effects of CACC on traffic flow an in depth research was achieved by van Arem et alii. A microscopic simulation were set up with the software MIXIC, which includes a sophisticated car following model. It has been simulated a 4-kilometer long highway section with four lanes, with a reduction to tree lanes at three kilometres. The traffic composition was based on data of the Dutch A4 motorway implemented, with 94 percent of passenger cars, light trucks 4 percent and 2 percent Trucks. That means that the simulation results represent rather the effects of CACC-equipped cars than for trucks. The interval of equipped CACC Vehicles (trucks, commercial vehicles and passenger cars) was 0.5 seconds and 1.4 seconds with conventional vehicles. There were six scenarios for mixed traffic from 0-100 percent CACC-equipped vehicles and four scenarios of 20 to 80 percent of CACC-equipped vehicles on a separate track. As a CACC-lane, a fourth lane was implemented. The equipment levels were increased between scenarios by 20 percent. Shock waves were the indicator of the stability of traffic flow in the study. This was measured on three consecutive vehicles within a maximum of 50 meters and a delay of 5 m/s^2 or more. In the simulations without a separate track, the number of shock waves ahead of the bottleneck reduced about 90 percent between the reference scenario and the scenario of 100 percent of vehicles equipped. At 20 percent equipped vehicles there was already a 30 percent reduction of the shock waves. After the bottleneck, the number of shock waves was also reduced, but not as much as before the bottleneck. The reduction of the shock wave number in the scenario with a separate CACC lane shows a similar pattern as previously described. The average speed before the bottleneck changes about 10 percent comparing the scenarios 0 percent and 100 percent of CACC-equipped vehicles. On the cross-section after the bottleneck no increase has been measured. Another interesting result of the simulation is that the average speed at low levels of equipment decreased. The simulations with separate CACC-lane show, in contrast to the scenarios with mixed traffic, higher speeds before the bottleneck and lower ones after the bottleneck. The vehicle throughput before the bottleneck is affected only slightly positive. Improvements between 60 and 80 percent of equipped vehicles are significantly. Simulations with separate CACC-lane show little impact on the throughput of vehicles and still less improvement than the simulations without CACC-lane. The simulations of the CACC-use with the concepts with and without its own CACC-lane show a differentiated result between the scenarios and the diffusion levels. At a high level of CACC-equipped trucks, the system improves the stability of the traffic flow and the average speed. These improvements also depend on whether the traffic density is high or low because in (a lot of) dense traffic there is more interaction between the vehicles, which is then modified by CACC. A separate track in combination with low levels of CACC equipment has adversely affected the traffic flow. At a high diffusion rate the CACC separate lane leads to improvements. The capacity at a lane blocking is improved only marginally by CACC [14, 1]. It should be emphasized that the traffic volume have not been varied regarding the capacity and that explains the results. The number of shock waves in traffic flow decreases through the CACC-use. A significantly decreased number of shock waves should increase the average speed and the capacity [15]. The average speed partially reduced and the capacity increased only slightly. Reasons for this are effects so that the traffic volume was not very high.

Falling speeds for certain grades of diffusion of CACC have already been shown in a work from 1997, which examined automated driving. Using a mathematical model it has been calculated that traffic volume on a route increases through the use of CAAC, however at low levels of diffusion (between 5-10 percent) it decreased slightly Though, the traffic volume in this experiment was not varied [15].

Concerning the travel time and the capacity, there are very different results from negative to negligible positive effects. There are currently no comparable results, because varying traffic densities, equipment levels, the simulation model qualities and constraints of very different conditions are present in the investigations. To summarize the results the effects of CACC for mixed traffic on two-lane highways will be negligible or slightly negative. The disturbance of the traffic environment and the possibilities for platoon formation affect the development of the effect of CACC. On three-lane highways that is no longer given and an increase in average travel time of 14 percent is possible. On a four-lane highway a 10 percent increase in average speed could be determined. It should also be noted that at low traffic volumes and low degree of equipment of the vehicles, travel times can be worse than without CACC. The establishment of separate CACC lanes only appears worthwhile at high traffic volumes and a large market diffusion of CACC, otherwise negative effects can be expected, while the investments for the expansion are high [3].

Results from cited researches show that the expansion of the number of lanes has its most obvious effects at high traffic volume and a high degree of equipment of vehicles. Concluding the review of existing results of the impact of CACC we can say that the system influences the traffic flow. But in fact, there is no discrete data on varying truck share and varying share of CACC-equipped trucks available concerning the impact on traffic flow. The further investigation of impacts of the modern CACC-System (up to 7 coupled vehicles with in distance of 10m) on traffic flow is needed to assess the opportunities of this modern transportation system to contribute to a more sustainable transport and the expected increase of traffic in the future. This paper aims to describe the results from a research where that kind of impact was investigated and close the gap.

3. Methodology for the Detection of the Impact of CACC on Capacity and Speed

A field investigation with equipped and non-equipped vehicles is one possibility to collect the data. This is a very complicated and costly method. An alternative is to simulate the real traffic flow. The necessary tools are available and well established in science [11, 4]. For data collection in this study the microscopic traffic model VISSIM is used. VISSIM is chosen first, it was available for this research and secondly the reliability of VISSIM is established by its application in many research projects which dealing with different kind of measures and their impact on traffic flow.

3.1. Design for the Investigation of the Impact on Traffic flow

The car-following model in VISSIM is based on the work of WIEDEMANN. It contains a psycho-physical model of the longitudinal movement of vehicles, lane changing operations and controls the behaviour within a lane.

In VISSIM, the properties of the track, the cars, the traffic situation and the driver are required to simulate the flow of traffic. For instance, the curviness of the route has no effect on the traffic in VISSIM. The track of the test site has a length of 5000 meters. Entrances, exits, construction sites, rest areas and other possible elements of highways are not implemented because of the use of CACC primarily outside these influences is seen. Therefore the infrastructure model could be prepared as a spiral (see Figure 1).

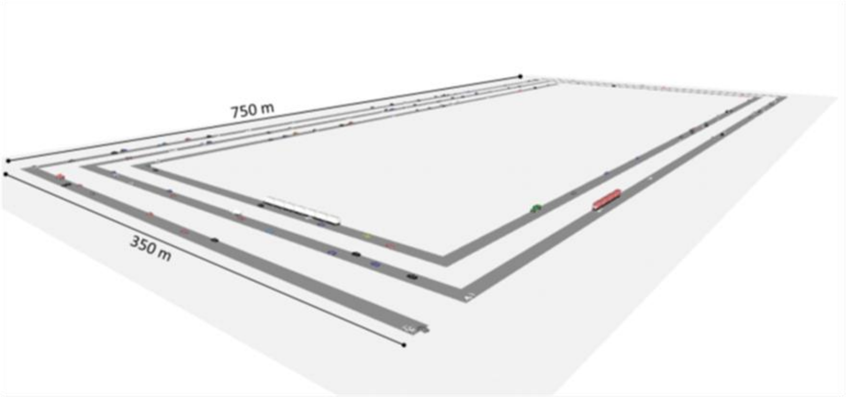

Figure 1:Test Site in VISSIM

In reality the slope of the road has an impact on traffic flow. This relationship is mapped e. g. in the German Highway Capacity Manual (HBS) (the HBS is the reliable base for the design of road traffic systems in Germany) [5]. In VISSIM, a tilt range can be set that affects the driving behaviour of trucks. In the simulation we will focus on the most common occurring road slope in Germany of <2 percent limit and in the scenarios the mean slope is set between 0 and 2 percent to 1 percent. The most likely expected use of the CACC system is that on three-lane motorways, because each time they enter the system on two-lane highways the platoon decouples [9]. Therefore a cross-section with three carriageways was implemented as a test site in VISSIM. The cross section itself doesn't have to be specified in VISSIM if the transverse behaviour of the vehicles is without any influence. This is realistic to motorways and is therefore dealt with in the model.

Detectors are implemented on the test site at three points ($x = 1000$ m, $x = 3000$ m and $x = 4800$ m) to ensure that the measurement result is independence of the of the detector location while increasing the amount of data per simulation. The detector records the average speed (v_{avg}) of cars over the duration of 300 seconds to the mean current speed and the number of all vehicles (cars and trucks). In the HBS idealized q-v diagrams (refer to the mean v_{avg} speed of cars and the number of cars and trucks) for different road types, truck portions and slopes of the road are provided. These diagrams are used to calibrate the model [5]. Thus, the collected Data from the model can be compared with the calibration data.

3.2. The Characteristics of the vehicles in the model

Four different attributes of vehicles are described in VISSIM: vehicle category, vehicle class, vehicle type and model of vehicle. The vehicle category has bearing on whether the track inclination and the mass-Engine performance ratio are taken into account when driving or not. Only for the category of trucks it is influencing the driving performance, for cars it does not. The driving behaviour of vehicles can be used for vehicle classes defined on a route. Likewise, the data detection can be differentiated by vehicle classes. Within a class of vehicles, the vehicle types are summarized. Each type of vehicle has the same technical characteristics as e. g. desired speed and desired acceleration.

In the model, three classes of vehicles have been implemented: Passenger cars, light trucks with a length of up to 14.4 m and heavy trucks together with tractor-trailers. The length of the different vehicle types are taken from an analyse of many detected vehicles on a German motorways [16]. Based on these data a classification of the occurred vehicle lengths into small groups has been made. Within each class, up to 10 vehicle models were implemented and create a detailed and realistic base within VISSIM to describe the dimensions of the vehicles. The selected vehicle classes are shown in Tableau 1. The three classes of vehicles were also set as the vehicle types in VISSIM, so that the driving performance and the technical characteristics of the vehicles within a class or one type are identical.

3.3. Calibration of the Model

To describe a target state of the calibrated model the idealized Traffic Volume-Velocity-Diagrams (q-v) from the HBS were used [5]. Because of the reputation of this standard literature for transport engineering in Germany the q-v-relationship is taken from there to validate VISSIM.

Tableau 1 Vehicle Classes and their Length

Nr in the modell	**Car**	**Car**	**Light duty trucks**	**Light duty trucks**	**Heavy duty Trucks**	**Heavy duty Trucks**
	Lenght [m]	**Portion [%]**	**Lenght [m]**	**Portion [%]**	**Lenght [m]**	**Portion [%]**
1	2.4	2.7	6.4	21.3	15.4	34.3
2	3.4	7	7.4	17.5	16.4	38.8
3	3.7	16.7	8.4	18.4	17.4	16.8
4	4	28.4	10.4	19.8	18.7	10.1
5	4.3	25.9	14.4	23	-	-
6	4.6	9.1	-	-	-	-
7	4.9	3.8	-	-	-	-
8	5.2	2.2	-	-	-	-
9	7	3.2	-	-	-	-
10	14.5	1	-	-	-	-
	Sum	100	Sum	100	Sum	100

For three-lane highways outside of metropolitan areas truck proportions of 0 to 20 percent were selected in the HBS. The calibration curves thus allow a state without and with truck traffic. The composition of the three vehicle models (cars, small trucks and truck tractors and articulated lorry) are implemented in a way that the truck share of a cross-section is 81.9 percent for tractor-trailers and articulated lorries and only 18.1 percent for small trucks. For statements on the influence of the parameters CC0 to CC9 on the capacity of each of these parameters between the minimum and maximum values were varied in a study [11]. Therefore reasonable limits of the parameters are described. Within these limits, we looked for the eligible parameters for a calibrated state of the model in this investigation. The setting of the in attention of motorists is at the calibration instructions from [6] based on the motorway traffic. The setting of the parameter of the transverse vehicle behaviour (like overtaking) has not been changed in VISSIM, so the standard is used.

As a first step in the calibration process, the pure car traffic has been calibrated. Subsequently, a truck portion of 20 percent is fed into the circuit and the parameters of the truck for a slope of 1 percent as the average slope calibrated between the HBS in the designated class of 0 to 2 percent. In the HBS q-v relationship with a truck share is reported by 10 percent. As a final step, the calibration parameters have been determined for the used truck shares, whereby, a match in valid parameters from the simulation with 20 percent truck share is between HBS and VISSIM data was shown and this should also be revealed.

The validation of the calibrated parameter occurred by an comparison of ideal-typical q-v curves of the HBS and the resulting curves by the simulation. The function, shown in Equation 1, was used to calculate the q-v curves out of the simulation.

Equation 1: Volume Delay Function of Müller [16]

$$t = f(q) = \frac{\beta - \left(\frac{q}{\gamma \cdot q_{\max}}\right)}{t_0\left(\beta - \left(\alpha - \frac{T}{\tau}\right)\left(\frac{q}{\gamma \cdot q_{\max}}\right)\right)}$$

$$\text{with } \frac{q}{q_{\max}} \leq 1, \text{mit T} = \text{Truck} - \text{Portion}, \alpha, \beta, \gamma \text{ as free parameters and}$$

$$\tau = 2 \text{ for two} - \text{lane motorways}$$

This function is a new development of so called Volume Delay Function which considers the decreasing passenger car speed in relation to the number of vehicles and also the proportion of trucks on road. This function can perfectly be fitted to the HBS curves (fitting by the method of smallest squares) [16]. The parameters of VISSIM has been taken as calibrated even if the fitted Volume Delay Function onto the data out of the simulation runs compared to the ideal-typical curves are below $R^2 > 0.95$. The final parameter set is shown in Tableau 2.

Tableau 2 Parameter of Driving Behavior of Cars and Trucks on a German Motorway

Name of the parameter	**Nr of the parameter in VISSIM**	**Car**	**Truck**
Stopped Condition Distance [s]	CC0	0.61	1.45
Headway Time [s]	CC1	1.09	1.66
Following Variation	CC2	3.05	1.5
Threshold of Perception	CC3	-4	-3.5
Pos. Following Thresholds	CC4	-1	-1
Neg. Following Thresholds	CC5	1	1
Influence of v on Oscillation	CC6	20	20
Oscillation of the Acceleration	CC7	0.25	0.25
Acceleration from v = 0 km / h	CC8	3.52	1.05
Acceleration from v = 80 km / h	CC9	1.5	0.8
Looking Forward Distance [m]	-	250	250
Duration of Inattention in [s]	-	3	2
Probability of Inattention in [%]	-	7	5.5
Safety Distance at Overtaking in [m]	-	0.4	0.6

3.4. Parameters of the Intelligent Truck

The telematics system CACC was organizationally and technically described and it can be used to describe the driver behaviour of trucks in VISSIM. Is the first car driven manually tuning the performance parameters of the first vehicle with which the calibration process present match for human drivers. The coupled vehicles follow at a distance of 10 meters automatically. As the vehicle sequence in VISSIM cannot be explicitly defined, they are randomly placed on the route, the vehicle groups are therefore not limited by individual vehicles depict. However, coupled vehicles are modelled as an over-long single-vehicle, without that it would lead to a decreasing quality on the car-following behaviour in VISSIM. All vehicles in association behave like the first, what is very realistic. It is a condition of CACC and also a necessary agreement by users of CACC. Coupled vehicles are therefore described by the manual behavioural parameters. The only difference is that platoons are not allowed to overtake other vehicles.

The process of platooning is modelled externally. According to [13] a maximum of seven vehicles is coupled in a platoon. The distance between the vehicles is 10 meters [9]. Because the convoy formation considers the ratio of the mass and the power for the CACC-equipped vehicles, theoretically all trucks can be coupled with each other, if the mass-power ratio of the output is matching or similar vehicles are coupled to each other. Which vehicles are coupled in a platoon is, therefore random. The number of vehicles coupled in the platoon is coincidental. The assumption of the randomness can be restricts by the term that the CACC system is foreseeable designed for a scenario for the deployment in heavy trucks, not in regionals operations. Following that, the system would also be used in vehicles that are primarily used for long hauls. They are already implemented in VISSIM as a third class of vehicle tractor units and articulated lorries. With this assumption in the modelling only trucks and articulated lorry (length > 14.5 m) are coupled in convoys. For the implementation of CACC in VISSIM also has also to consider the probable number of vehicles will be answered in a bandage. According to [9] the most likely variant to practice is, that the CACC-use is organized the convoy drivers. That means that the CACC system is searching for suitable vehicles in a certain radius by the on-board unit. Even the date at rest areas for platoon of education seems to be realistic. That appropriate vehicles are found can be assumed but also depends on the enforcement of the system. But it is possible that other vehicles or two platoons can be coupled while driving a (e. g. with two plus three vehicles). So, coupled vehicles with higher vehicle numbers cannot be excluded. In this Sense, all variants have an equal probability (p = 1/6), if no further information is present. By multiplying the probable length L_{CACC} of the platoon with the probability of the number of vehicles, we obtain the probabilities of the single platoons (see Figure 2). If we take the vehicle length from Tableau 1, it can be the lengths of the single platoon to the individual vehicle lengths and the number of vehicles according to equation determination. This leads to 24 platoons distinguished by their lengths and probabilities of occurrence in VISSIM, but the possibilities between the minima and maxima as a representing length.

$$L_{CACC} = d(n-1) + n \cdot L_{Tuck}$$

With L_{Truck}= length of a single truck, d = distance between the truck and n is the number of Trucks in the Platoon

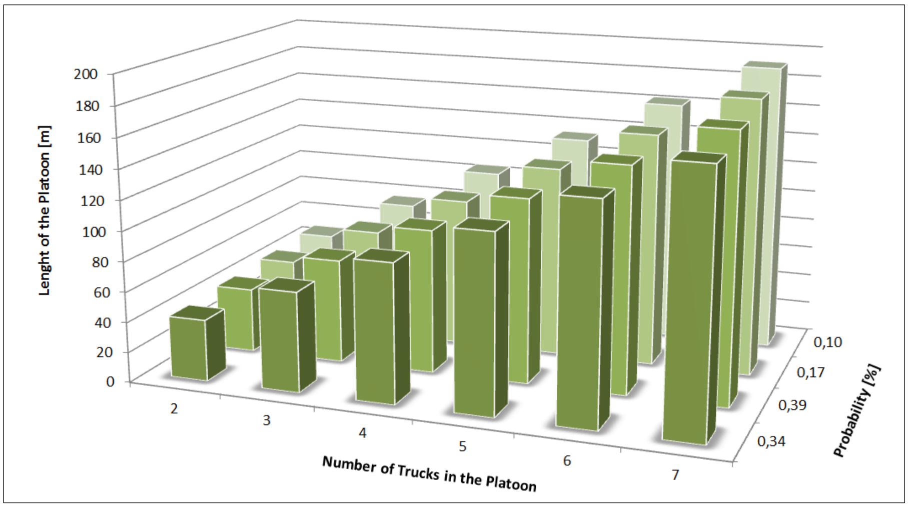

Figure 2: Set of the platoon lenght in the simulation

3.5. Definition of the simulation scenarios

The goal of data collection is to provide data for the investigation of functional relationships between the degree of heavy-duty trucks equipped with CACC and the resulting impact on the travel time and capacity. This requires that a range for the CACC-grade equipment and truck share is identified for which the data is determined. The grade of CACC- equipped vehicles here lies in the range of 0 to 50 percent. If the CACC equipment would be at higher levels separate tracks as an economical variant may also be considered (see [14, 1]). For the truck share a range of 0 to 25 percent is selected. Even if the truck shares represented in the scenarios are very low, they clearly have less impact. Extremes of very high levels of equipment and very high shares of trucks are not part of the scenarios. We can conclude that moderate conditions were simulated. The measured data has a random character, since the vehicles (cars, trucks and CACC equipped Trucks) are combined. Other stochastic effects are added by the fact that the order of the vehicles will be changed according to the simulation (VISSIM variable: start random number) and that the collection takes place at three measuring cross sections. Statistical certainty in the measurements is obtained by a large number of generated measurement data. Therefore there are scenarios, each with 1000 runs, and each simulating a different traffic composition. Based on these data q-v measuring data for various truck shares and shares of CACC-equipped trucks can be selected from a database.

4. Results of the simulations

Resulting from the simulations about 1.3 million records were stored in a database, which can be evaluated according to CACC and truck share content. The evaluation was done for the truck share of 0 to 25 percent and CACC-use equipment from 0 to 50 percent. Volume-Velocity-data (Q-V-Data) from all data sets which met the conditions, that they possess a certain truck and CACC-share were read from the database. It levels were evaluated by steps of 5 percent. For each level, a range of the truck and CACC shares of + / - two percent was admitted (5 % to 7 % = 3, = 8 to 10 % 12 %, etc.). Through this approach, all records from 0 to 25 percent truck share and 0 to 50 percent CACC-share have been considered. In the calculation of the truck and the CACC-share and the traffic volume coupled vehicles that are implemented as a vehicle in VISSIM have been considered. The Data collection occurred in VISSIM per vehicle class. For the vehicle groups 2 to 7, coupled vehicles were defined. In the calculation of the truck and the CACC-share within the traffic volume we have considered the number of trucks coupled multiplied. It was solved by multiplying the vehicle class with the number of the coupled trucks within a class. The velocity of the cars was measured over 5 minutes (quasi-instantaneous).

The data can now be examined regarding the effect CACC equipped trucks have on traffic flow. To determine the effects the data was first processed for interpretation. This means that a function has been adapted in its parameters to the data so that the amount of data is represented by a function curve. The function was the same as for the calibration process (see equation 1). To elaborate the new parameter of this function the data sets were used to fit the function in their parameters on the data by the method of the smallest squares. Methodically, the use of altered functional characteristics determined the change in the capacity and speed. For each of the changes from baseline the function value without influence CACC was determined (see Figure 2).

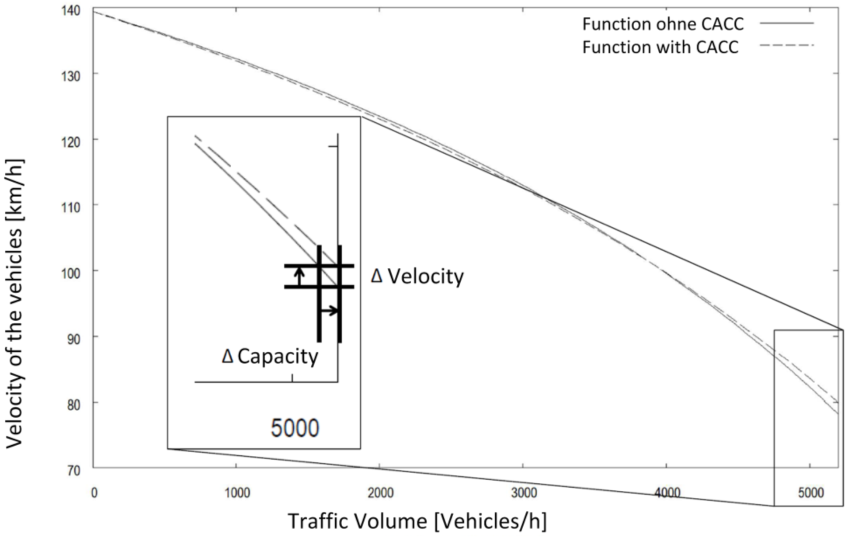

Figure 3: Methodology of the evaluation of effects of CACC

The final statements of changes are shown in percentage terms (see Tableau 3 and Tableau 4). An example of the results is given in Fig. 4, were for 10 % truck and various CACC equipment rates the curves of Q-V are shown.

When evaluating the data through an effect of the CACC on the road´s capacity can be determined. This means that in the simulations with an increased CACC Traffic flow, traffic can pass through the route, without the traffic collapses. This Effect is remarkable, however, only with higher proportions of CACC convoys. At 10 percent Truck share and 50 percent trucks CACC coupled together, an increase of capacity by 4 percent is calculated. In the scenario with a truck share of 25 percent in the traffic flow, of which 50 percent are equipped with CACC, the capacity has been increased by almost 6 percent. Thus this is the most obvious effect on traffic flow that could be measured for CACC. In Tableau 4 increases in capacity for truck shares of 5 to 25 percent and equipment levels of 25 and 50 percent are shown.

The average car speed is increased by the use of CACC in heavy trucks, the largest increase – 6.4 percent - is at 15 percent truck share and 50 percent CACC-equipped trucks. At 50 percent in equipment and truck shares from 10 to 25 percent average speed increases between 5.5 and 6.4 percent. So it must be noted that the influence of high levels of equipment about the same speed on the car works. The well-known relation between truck share and car speed as it is shown in HBS [5], weakens under the influence of CACC. It can be

Tableau 3 Impact on Car-Speed for Different Truck Share and Equipment-Rates

Truck-Portion	CACC-Portion 25%	CACC-Portion 50%
5 %	1.23 %	3.70 %
10 %	2.28 %	5.70 %
15 %	2.75 %	6.38 %
20 %	1.95 %	5.50 %
25 %	1.25 %	5.56 %

Tableau 4 Impact on Capacity for Different Truck Share and Equipment-Rates

Truck-Portion	CACC-Portion 25%	CACC-Portion 50%
5 %	0.77 %	2.11 %
10 %	1.66 %	4.11 %
15 %	2.48 %	5.45 %
20 %	1.88 %	5.06 %
25 %	1.39 %	5.75 %

explained by the disturbance of cars flow (e.g. overtaking) becomes less with fewer single moving trucks. At lower proportions of equipped trucks there is a slightly more positive, but negligible small effect. One can state that very long vehicles do not affect traffic flow negatively. On the contrary, it is preferable on three-lane highways that trucks drive in convoys with small driving distances. However solely propelled trucks influenced the car traffic partly significantly negative. Setting the measurement points in an ideal-type function using the method of least squares changed the course of the q-v-data is not relevant. The graph is somewhat flatter, which explains the capacity expansion and increase in speed (see Figure 4).

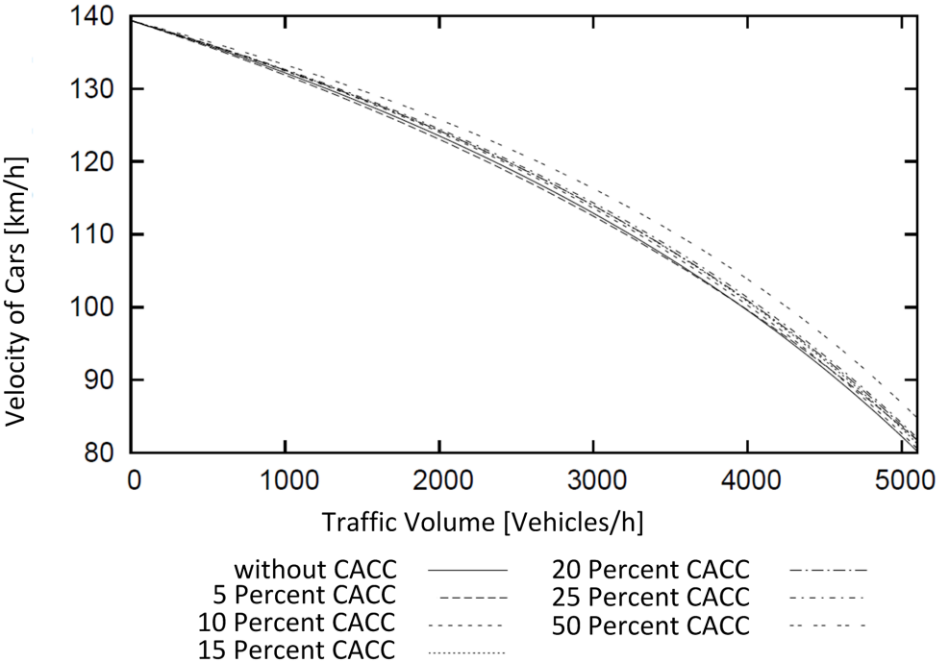

Figure 4: Q-V-Curves at 10 % Truck share and various equipment rates with CACC

The effects of CACC equipped Trucks on traffic flow for three-lane highways that could be identified in this work can be, characterized by the following key points:

- The roads capacity can be increased by up to 5.5 percent.
- High truck shares and high equipment levels show the greatest effects on the capacity. If one of the two parameters decreased, the effects on the capacity of the route were reduced.
- The average car speed increases up to 6.4 percent.
- The increase in car speed is quite similar for different truck parts.
- The effects are non-linear.
- The capacity is virtually unaffected at low levels of equipment.
  There were no adverse effects on traffic flow at high or low equipment levels detected.

The effects on traffic flow of CACC for trucks arrange with the findings of other telematics research projects. Thus for the driver-assistant system in the CHAUFFEUR II project for an equipment rate of 40 percent an effect on the capacity of a three-lane highway of plus 3.6 percent has been determined. The simulation of a bottleneck on a Dutch highway with a truck-share of 4 percent showed and CACC various equipment levels for all vehicles (cars and trucks) showed a slightly positive effects of up to 5 percent on the speed. Even there, it was figured out that the speed did not uniformly increase, but that at intermediate levels of equipment between 20 and 60 percent the increase is lower than at high levels of equipment. It is interesting that this result represents the reverse of what was stated in this work, that for moderate levels of equipment the greatest effect on speed was registered. But it must be taken under consideration that the conditions differed considerably: not only trucks but all types of vehicles were equipped with CACC, the tuck share was two percent and a bottleneck situation has been simulated. Therefore the results can only be used for comparison.

All previous results are based on microscopic simulations. There were different simulation programs used and conditions modelled. It can thus be stated that the simulation results lie in a range, which is plausible.

5. Discussion of the results

The results of the simulation figures out, that an increase of the capacity and the passengers cars speed is possible. But the capacity of a road is not a fixed value and can vary by the drivers, the vehicles, the weather condition etc. Therefore, the capacity is to consider as a stochastic value. Within the simulations stochastic effects has been taken in account by following aspects:

- Number of vehicles and vehicles behaviour in VISSIM
- varying the composition of the traffic flow by achieving many simulation runs
- detection of the data at different cross-sections
- detection of indication in 300s interval what composes an average (in reality and simulation)

Therefore, from that point of view, a high validity of the results can be assumed. A critical point of the simulation is, that all the drivers (cars and trucks) did not change the driving behaviour between the scenario without and with CACC. That is unrealistic because of an introduction of that kind of high sophisticated system like CACC is, a change in the entire transport system can be assumed. For example if CACC is permitted for the deployment someday, other supporting Advanced Driver Assistant Systems (ADAS) are in use by the cars high frequently. The tendency of the increasing use of ADAS can be observed since years. But difficulty is how to describe the total change of driving behaviour in the future with all possible influences? Therefore the results has to be interpreted with ceteris paribus conditions. It is what we could achieve as a part of that what the reality will become.

6. Conclusion

The research considered the question what the impact on the traffic flow is when heavy duty trucks are equipped with the Cooperative Adaptive Cruise Control System. Therefore a simulation was chosen as the method to obtain the needed data which has been not available before. The data figures out that an increase of the passenger cars speed is up to 6.4 percent possible. The total capacity of the road can be increased up to 5.5 percent by the platooning of trucks. Simulating traffic flow we can see that it is possible to increase the efficiency of a three-lane highway when heavy trucks and trailers drive CACC-equipped.

This enabled the determination of environmental effects of truck platoons on three-lane highway traffic. Not only if we consider the capacities effect is an environmental effect also given by the known effect of driving in smaller distances and the decrease of fuel consumption (e.g. the American PATH project is investigating the topic of fuel consumption and platooning).

Of particularly high interest is the derived statement, that the extra-long vehicles will not disturb the traffic flow on the six-lane highways. In the investigations results this can be stated by low equipment rates of the trucks with CACC but also an increase of speed and the capacity. Especially the European and especially the German discussion about the Mega-Trucks/Giga-Liner can be affected by the presented results.

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