

# **Traffic and Vehicle Technologies**

## **Assessment with the Simulator PELOPS**

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### **Abstract**

At the ika the submicroscopic traffic simulation program PELOPS (Program for the dEvelopment of Longitudinal micrOscopic traffic Processes in a Systemrelevant environment, <http://www.pelops.de>), was developed in co-operation with the BMW AG (1). It simulates the traffic flow on motorways with a specific view on vehicle affairs. One application for PELOPS was the assessment of ACC (Adaptive Cruise Control) systems inside the PROMETHEUS program. A new research period extends the use of ACC about the functionality in urban areas. This requires an extension of PELOPS about some specific models. With this extension, it is possible to analyse new traffic technologies for individual vehicles or infrastructure. Based on detailed traffic measurements, different scenarios are simulated to improve the traffic flow and to relieve the environment. These scenarios include ACC systems, inter-vehicle-communication and intelligent traffic lights. Another actual application is the analysis of the influence of new road trains (extra-long trucks with increased speed and enhanced breaking-capabilities) on traffic-flow and driving safety on German motorways. The paper gives detailed information about the simulation techniques and the results of the current analysis.

### **1 Introduction**

Current research leads to a reorientation from an isolated view of the vehicle to the vision of the „intelligent vehicle“ on an „intelligent road“. Thus a variety of systems concerning the influence on traffic were developed in the frame of the European research programs DRIVE, PROMETHEUS and the German program MoTiV. These systems refer to collective (concerning the complete traffic) as well as to individual (concerning the single vehicle) methods to influence traffic. For an early assessment of these advanced vehicle and traffic control systems the simulation of traffic flow is used. It allows, by means of a virtual picture of the traffic, to give inexpensive, secure and reproducible statements concerning the influence on the course of traffic.

### **2 The Simulation Tool PELOPS**

PELOPS was developed at the ika in co-operation with the BMW AG. The idea of PELOPS is a combination of high detailed vehicle- and traffic technical models, that permit investigations concerning the longitudinal dynamic of vehicles as well as an analysis of the

course of traffic. The advantage of this combination is the opportunity to take all interactions into consideration that occur between driver, vehicle and traffic. An important basis for the realisation of this idea is the fact, that the computer capacity was significantly optimised during the last years. Without this capacity the required degree of detail with a simultaneous consideration of all influencing factors would be unthinkable.

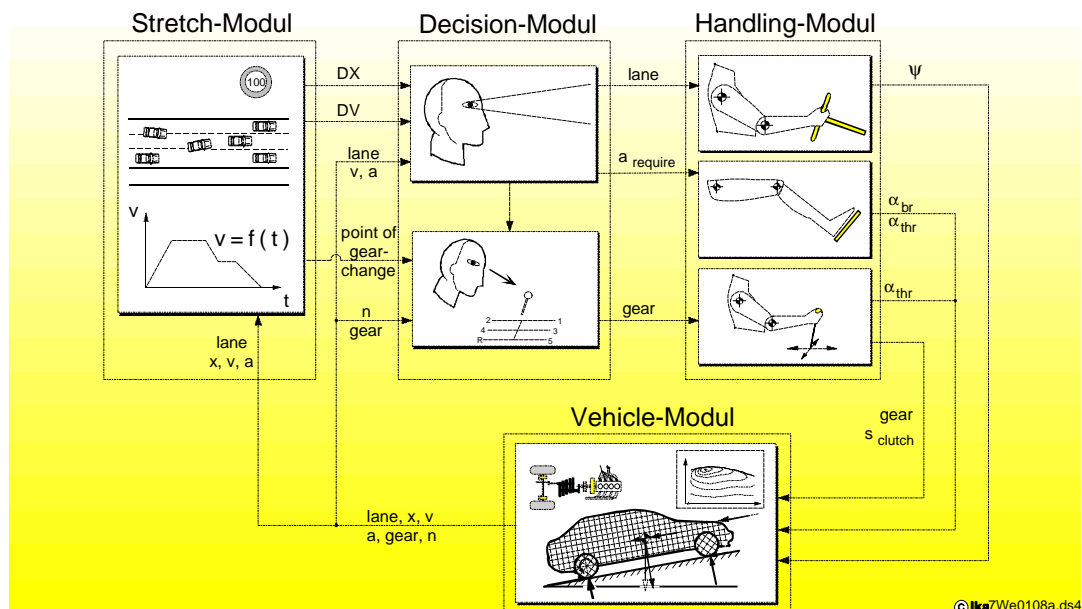


Figure 1: PELOPS main structure

PELOPS is orientated towards the fundamental elements of traffic, namely route and environment, driver and vehicle (Fig. 1). The route model is based on the presentation of the altitude profile with gradients, further on the presentation of the curves with straight stretches of road, arcs of a circle and transitions from a straight route to a curve, as well as of the number of lanes with the respective lane widths. In addition to the geometrical course of the road, the sign postings and the environmental conditions define the state of the route. The route-model covers the entire range from motorways to urban roads, including for example intersections and traffic-lights. The marginal conditions of the traffic situation result from the instructions concerning the number of vehicles that drive on a certain part of the route with a defined length (traffic density) as well as from the starting speeds and the distances between the vehicles (traffic flow). To produce certain courses of traffic or to instruct vehicles with calculated load profiles, single driver-vehicle-units may also be moved according to specific driving speed profiles. In regard to investigations on single vehicles this can be realised by means of standardised driving cycles, like 'EUDC', 'FTP-75' etc. or in traffic investigations by means of e.g. breaking in panic or constant driving. Figure 1 shows the four main modules of PELOPS and the principle interaction between the models.

## 2.1 Vehicle Model

The vehicle model is based on the 'cause- and effect-method' (2), which means that the order of calculation is based on the operating point of the engine (speed of rotation rare and load) and continuous over the clutch, transmission and differential to the rotor gears where the tractive- and resistance powers are balanced. (Fig. 2) The operating point can be changed by altering the load (cause), that is adjusted by the driver and that leads to a change in power and therefore to a change of the speed of rotation rare (effect). The behaviour of the engine is described by means of characteristic maps including e.g. data about the engine's torque, fuel consumption or emissions.

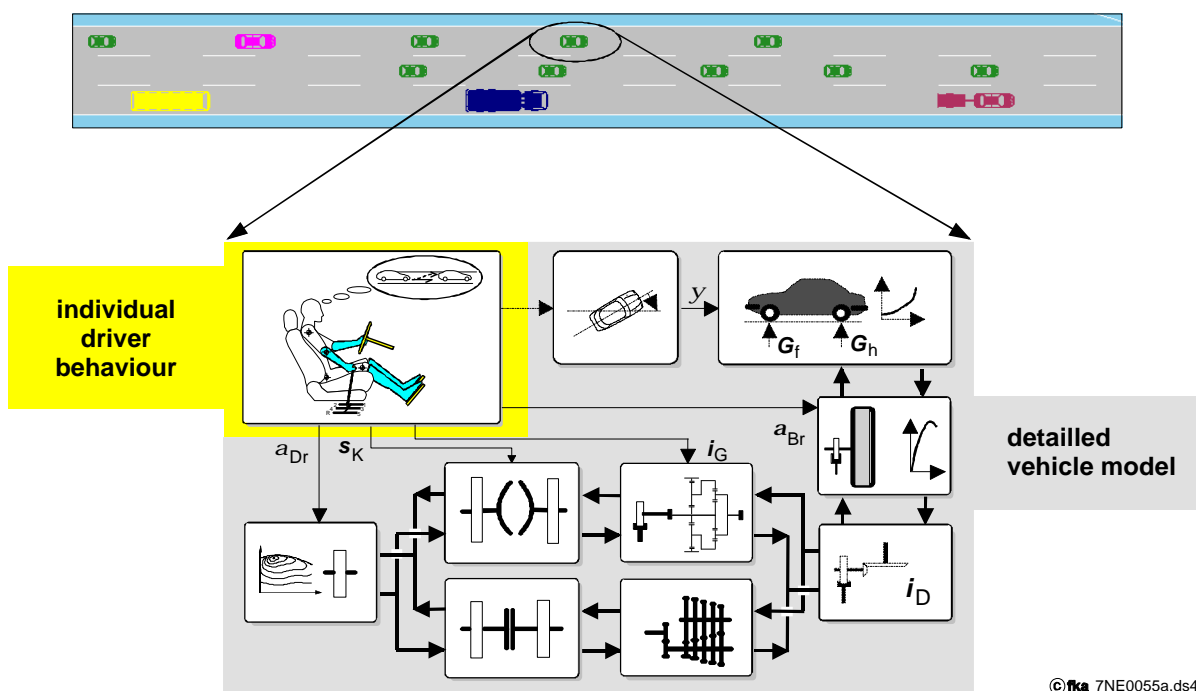


Figure 2: PELOPS vehicle model

The implemented transmission designs are a conventional manual- and an automatic transmission model with a hydrodynamic converter. At the transmission output a retarder model for the simulation of trucks is available. The presentation of the vehicle in this manner according to the cause- and effect principle makes the analysis of autonomous vehicle systems (intelligent cruise control, ABS, etc.) possible.

## 2.2 Driver Model

The driver model presents the connecting link between the mere vehicle- and the traffic simulation. It is divided into a 'decision-' and a 'handling level'. On the decision level a driving intention is determined based on the driving condition and the traffic environment and consists of acceleration, choice of lane and gear and a strategy-level for reacting to intersection, traffic-lights etc. To ascertain the driving intention, PELOPS works with a

psycho-physic distance model, which divides different ranges of driver's behaviour by means of reception thresholds. On the handling level the respective intention of the driver is calculated in the corresponding positions of control elements. In this respect the accelerator- and brake pedal are united into a drive pedal. The drive pedal is controlled by a PI-control algorithm. The change of gear takes place with time and torque control; in this case every driver has individual times for the gear change. During lane change one deduced from the crosswise dynamic. The vehicle is moved alongside a sinusoidal curve from one lane to the other. The shape of the curve depends on the kind of lane change, which is again individually calculated for the driver and the vehicle.

### 2.2.1 Following Behaviour

The basis of the driver model is a psycho-physical follow the leader model. It has been introduced 1974 by Wiedemann (3). For the application in PELOPS this model had to be developed further and extended substantially (4,5,8). In PELOPS the driver is described by typical parameters, such as reaction time, level of perception, level of attention, the need for safety etc. Furthermore the model used in PELOPS distinguishes between different driving situations depending on the surrounding traffic situation and the environment.

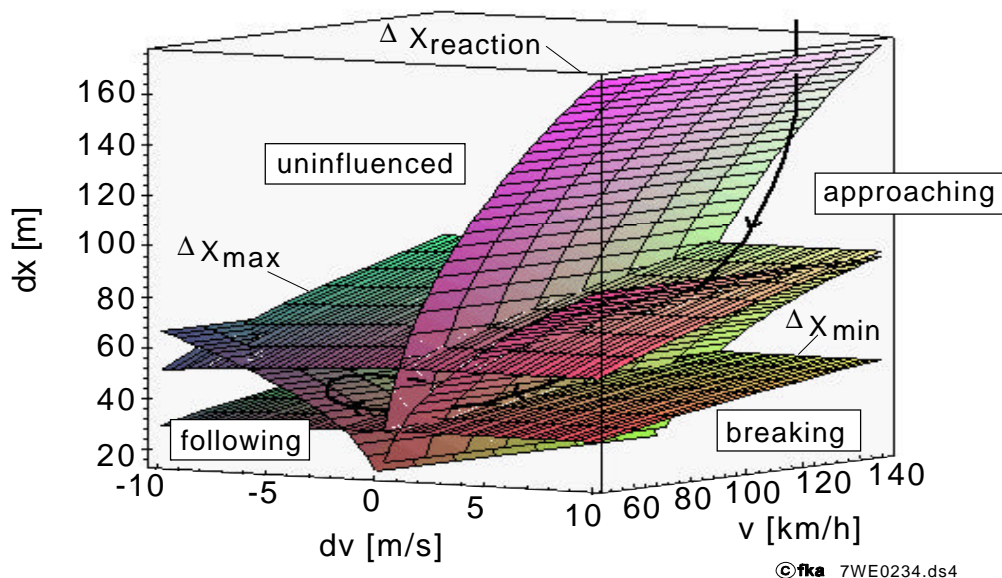


Figure 3: Driving situations and levels of perception

The parameters of the driver model are adapted to four different driving situations in which drivers behave significantly different: *uninfluenced driving*, *approaching*, *breaking in emergency situations* and *following*. Depending on the actual vehicle speed, the distance and the differential speed to the preceding vehicle the PELOPS driver model calculates an individual desire for acceleration or deceleration (Fig. 3). As soon as the individually desired following distance is reached, the driver model switches to following mode. A limited control of the acceleration pedal, e.g. due to lack of concentration or driver-errors in gap estimation,

leads to distance variations between the minimum and the maximum „following distance“ (see Fig. 3,  $\Delta x_{\min}/\Delta x_{\max}$ ).

The described PELOPS model of the driver's behaviour is used during „standard driving situations“. Depending on different traffic situations (e.g. approaching intersections or driving in a traffic jam), the driver's behaviour has to be modified to reach the demanded model-accuracy. Therefore a so called model of „tactical driver's behaviour“ was developed which adjusts the driver model to different traffic situations.

### 2.2.2 Tactical Behaviour

To adjust the driver's behaviour, the actual traffic situation has to be analysed in a similar manner as the human driver does. That means characteristics like range of visibility or reaction to surrounding vehicles have to be implemented. Figure 4 shows an example of a traffic situation which is analysed by the „tactical driver model“.

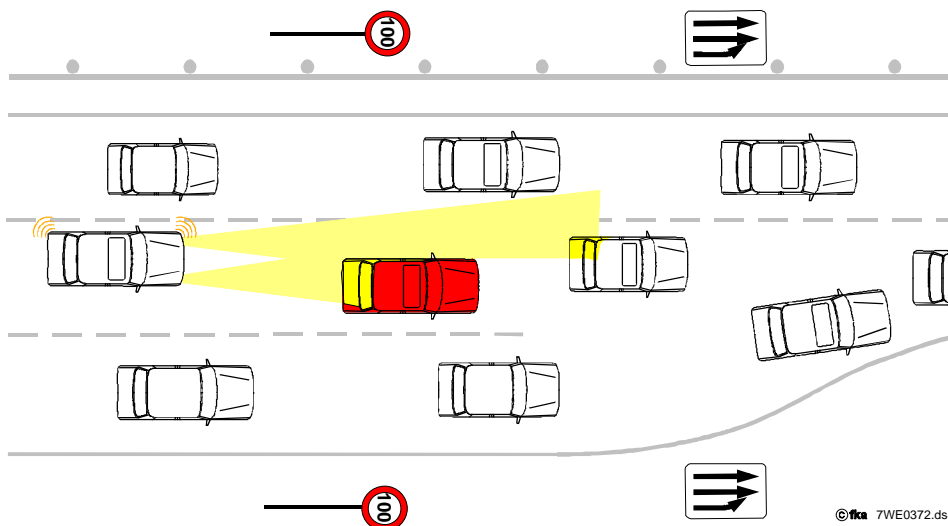


Figure 4: Detection of traffic situation

The analysis takes e.g. traffic-signs, reduction of the number of lanes or overtaking vehicles into account. Based on this, an adjusted desire for accelerating or lane-changing is calculated. Figure 5 shows the basic principle of the modelled lane-changing decision. For a various number of lane-changing situations (normal driving, merging, ending of a lane etc.) the parameters of the model are adjusted differently to consider the varying driver's behaviours.

Depending on the driver's contentness on their current lane a desire for lane-changing is determined. If the gap in the neighbouring-lane is large enough, the driver model will initiate a lane-change. The gap is dependent on the differential speed between the vehicles and the driver's individual need for safety.

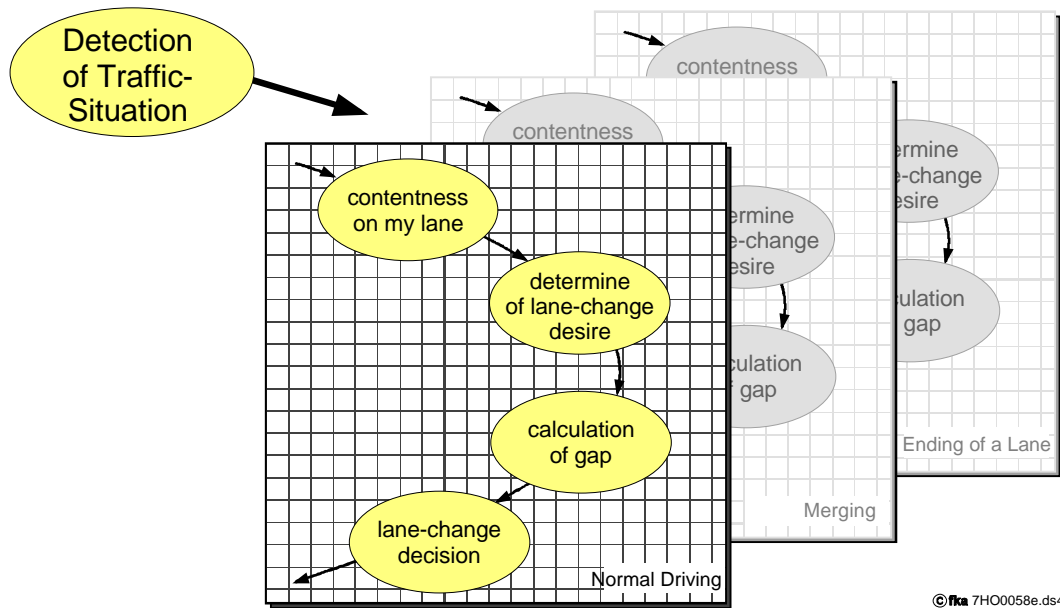


Figure 5: Structure of the lane-changing model

PELOPS offers highly detailed models for driver, vehicle and environment and draws in this way a virtual picture of real traffic. The accuracy of the calculated results were validated for various situations in urban traffic (6) (also see section 3.2 of this paper) as well as in highway-traffic (4,7). Combining the driver’s model with a vehicle model, based on the principal of „cause and effect“, enables the comprehensive analysis of advanced vehicle control systems like ACC (Adaptive Cruise Control) (see Fig. 6) as well as advanced traffic technologies.

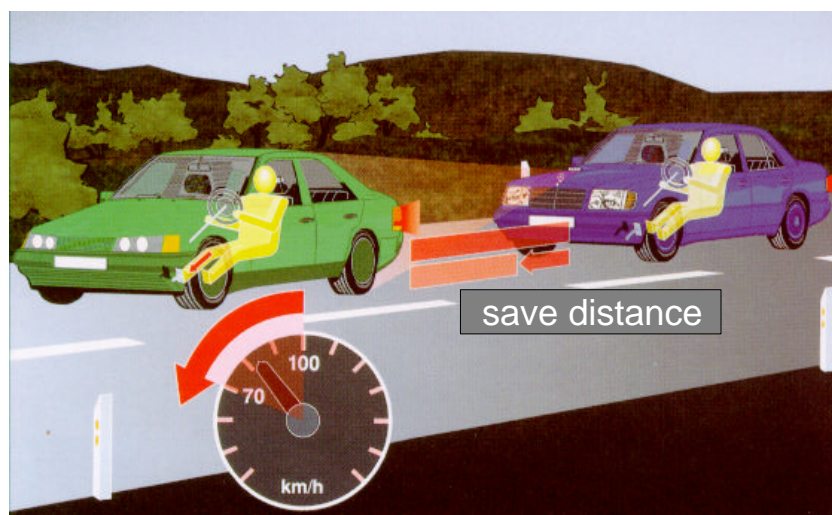


Figure 6: Adaptive Cruise Control (ACC) (PROMETHEUS)

### 3 Analysis of new Traffic Technologies

The development of ACC-systems has started more than fifteen years ago and has now reached nearly series-production readiness for highway-applications. During the European PROMETHEUS-program, simulation was a major tool to assess different ACC-systems. Questions about traffic safety, platoon-stability and impact on traffic-flow as well as fuel consumption or emissions have been answered by the use of the simulation-tool PELOPS (7). Current development focuses on systems which cover the entire range of situations from stop-and-go to complex urban traffic and intelligent traffic technologies.

#### 3.1 Optimising through Highway ACC

The following paragraph shows some PELOPS-results of the assessment of highway ACC-systems during the PROMETHEUS-program (7).

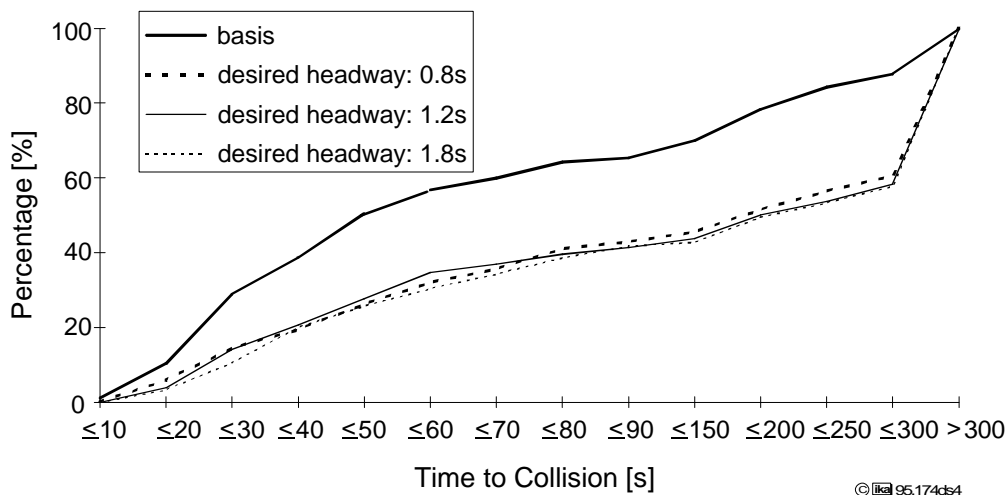


Figure 7: Time to Collision distribution

The effect of ACC on the traffic safety can be represented by the 'Time to Collision' (TTC), which is calculated with the speed difference and the distance. Figure 7 compares the TTC distributions.

In this diagram, the effectiveness of ACC becomes obvious. The system reduces the percentage of low TTC with the result of an improved safety. The TTC reduction can already be noticed in the lowest category up to 10 s. This tendency continues in the other lower TTC categories and causes an increase of the TTC in the upper categories. The reduction of low TTCs is highly important as they are the most critical for accidents. This tendency applies to all ACC-headways. The main reason for this effect is to smooth the traffic where speed differences are reduced, so that the TTC becomes larger.

The ACC effect on the road capacity is finally represented in figure 8: The diagram plots the average speed and the traffic flow for the different kinds of ACC-headways (40% vehicles

equipped with ACC). Capacity improvement means that speed and traffic flow figures are above those plotted in the curve without ACC. This only applies to the headway of 0.8 s. With a desired headway of 1.2 s, the situation comes close to the original situation, whereas the capacity deteriorates on a 1.8 s headway. An explanation of this can be found in the headway distribution. It is striking that only the headway distribution of 0.8 s is below the average measured headway distribution and for 1.8 s the headway is larger than the measured figure for which the capacity deteriorates.

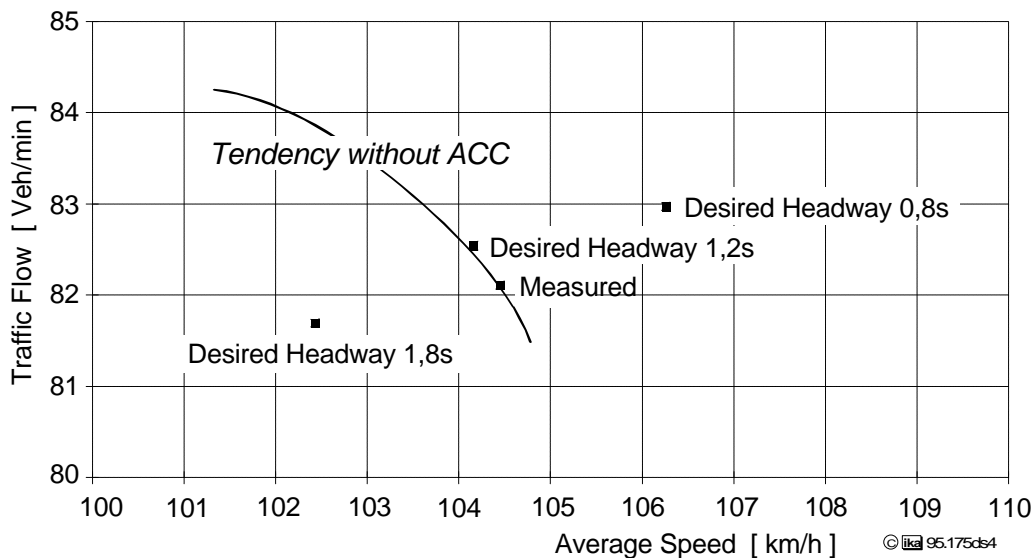


Figure 8: Fundamental diagram, highway traffic

### 3.2 Simulation of urban traffic

The above described analysis concentrated on highway ACC-systems. Current development focuses on systems which cover the entire range of situations from stop-and-go to complex urban traffic. Therefore, as a starting point for the assessments, a representative suburban area with high traffic load near the city of Aachen in Germany was chosen. This suburban area consists of three intersections controlled with fixed-phased traffic-lights. The total length of the area is 1600 m (Fig. 9):

With the help of video recordings and cruises in a measuring vehicle, an abundance of measurement data was collected in the Aachen-Lichtenbusch suburban area. The data analysed was collected during the rush hour on a working day between 7:20 and 7:40 am. A PELOPS basic scenario was drawn up from the measured data in such a way that marginal conditions for measurement and simulation are identical. Width of the lanes, length of the stretches of route, visibility range and phases of the traffic lights - they all correspond to reality. Exact maps of the area and control-programmes of the traffic lights were kindly provided by the Aachen City Council. The duration of the simulation (20 minutes) is identical to the period in which the measurement took place. Observation area I,

junction of ‘Oberforstbacher Straße’ (see figure 9), was chosen to evaluate the simulation results. Figure 10 compares the results to measurement data.

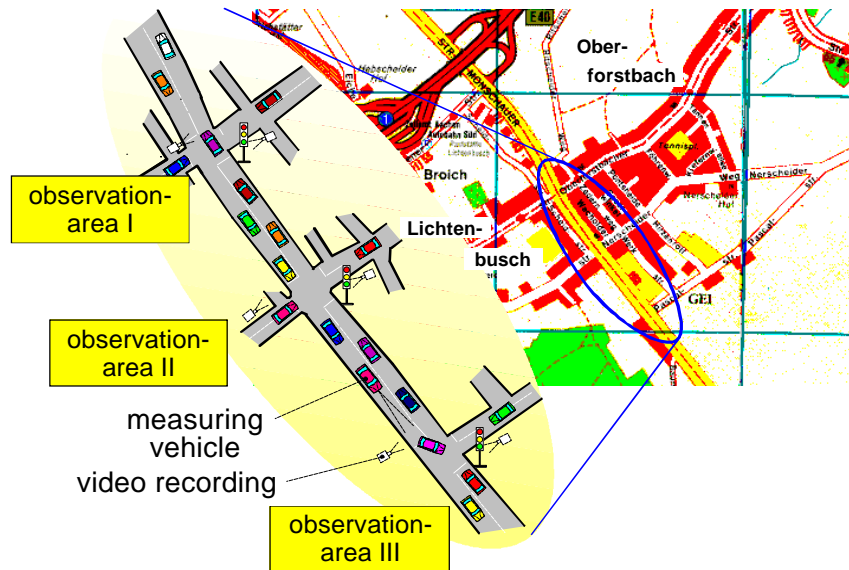


Figure 9: Suburban area of Aachen-Lichtenbusch, Germany

The comparison of measurement and calculation shows a high rate of correspondences. The calculated average speed in the investigation area is only 0.2% above the measured value. The speed distribution varies more severely than the average speed. Partly, these differences result from the measurement method.

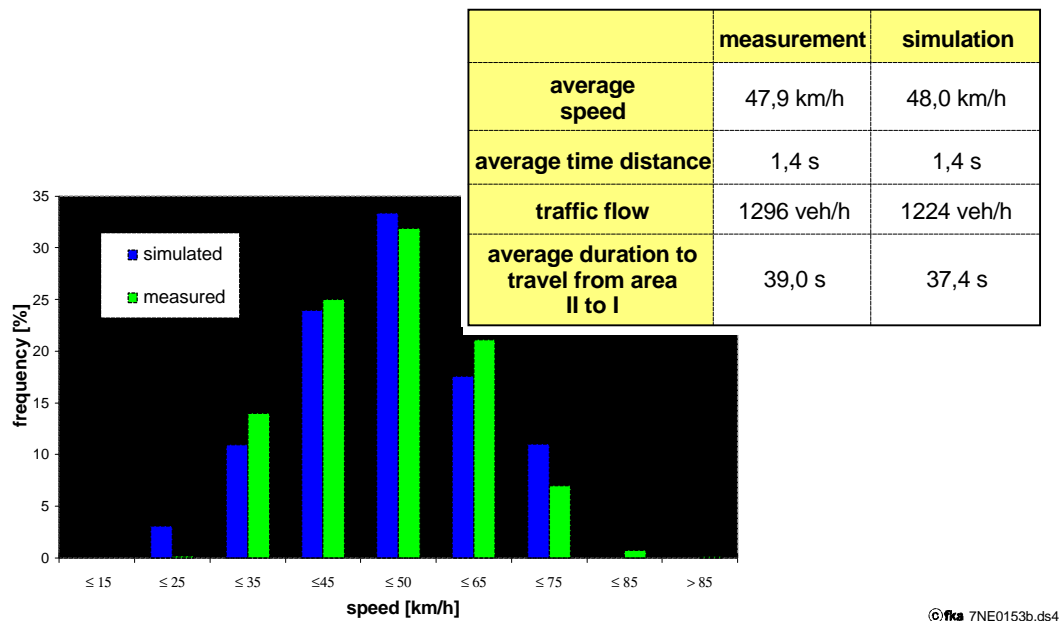


Figure. 10: Comparison of PELOPS simulation results of the basic scenario and measurements

The speed check procedure using a video camera evaluates a stretch of 8 meters, the simulation analysis, however, is limited to a single measuring spot. The traffic flow in the observation area is mainly determined by the traffic light phases. The deviation from simulation and measurement is therefore only minimal. The travel time defines the amount of time that is needed for a vehicle to get from observation area II to observation area I. It summarises all other traffic figures into one assessment criterion and allows an evaluation of the simulation as a whole. The comparison of measured value and calculation ( $\Delta=1.6s \approx 4.2\%$ ) shows that a realistic simulation of this criterion could be achieved.

To sum it up it can be noted that PELOPS cannot only represent the movements of single vehicles realistically (1), but also those of a complex traffic situation in a suburban area.

### **3.3 Optimising through urban ACC-systems**

First two different concepts of ACC-systems, suitable for urban traffic, have been developed. The first concept basically uses a simplified controller-algorithm that bases on an algorithm developed at the ika for the application on motorways. The parameters of the system needed to be adjusted to the new regulation task and the low speed level. Aim of the development of this ACC-system was to regulate the target distance with minimal deviations and short time lags. Thus, this controller is optimised for maximum traffic-flow. The disadvantage of this controller is, because of the required high accelerations and decelerations, less driving comfort that may not be accepted by the human driver. The second ACC-concept is oriented to the real driver-behaviour with smoother acceleration-characteristics and improved driving-comfort.

In the beginning the affectivity of these two urban ACC-concepts were investigated with PELOPS for one single intersection with traffic-lights. The throughput of a junction with traffic lights can be increased a lot if the starting behaviour of the convoy of vehicles can be optimised. The time needed for one vehicle to cross the stopping line is determined by the starting reaction time and the acceleration behaviour of the driver. Reaction time and the characteristic of acceleration can easily be optimised by automating the starting process. Apart from an increase in throughput such a measure may have another positive side effect, namely the reduction of strain for the driver and with that an increase of the driving comfort. The simulated optimising scenario consists of 14 vehicles equipped with the two ACC-systems. All vehicles are equipped with automatic gear-box to make the automation complete. The convoy starts after the light signals turn to green. After about 14 seconds, 10 ACC-concept-1-equipped vehicles (aim: maximum throughput) have passed the set of lights, whereas in the same period of time only 7 unequipped vehicles could cross the stopping line. The average increase of the throughput is therefore 44%. The vehicles equipped with the second ACC-concept (aim: maximum driving comfort) are showing only a minimum of throughput improvement.

Conventional ACC-systems measure the distance towards the preceding vehicle with the help of a sensor attached to the front of the vehicle. The controller only reacts to the course of route of the vehicle in front. This solution is of disadvantage for the automation of the starting process as the reaction times for starting of all vehicles in the convoy are added up. If the controller reacts to the first vehicle in the convoy, however, further increase of the throughput at traffic light junctions is possible. Intervehicle-communication allows information about the commencing of movement to be transmitted from the first vehicle at the lights (leading vehicle) to all other vehicles in the convoy simultaneously. The leading vehicle therefore transmits its current position and speed to the following vehicles. The data transmitted serves as input data for the ACC-controller 1. The ACC-controller 1 (aim: maximum throughput) introduced before needed not be modified. Again, the simulated scenario consists of 14 vehicles with automatic gear-boxes. The convoy starts after the lights change to green. As can be seen in the simulation results, the introduction of intervehicle-communication can increase the throughput of a junction with traffic lights. After about 11 seconds 10 vehicles equipped with the communication system have passed the lights. The same number of vehicles with the conventional ACC-controller needed 14 seconds for crossing the stopping line. The throughput of the stretch of road is increased by 8% compared to the conventional ACC-controller 1 and by 52% compared to the measured throughput.

In the second step the effects on traffic flow for the hole suburban area 'Aachen-Lichtenbusch' is simulated with PELOPS. Table 1 shows some results.

improvement	ACC 1	ACC 2
traffic flow	+12 %	+14 %
average speed	-13 %	+6 %

Tab. 1: Improvement of throughput and average speed through different urban ACC-concepts, 100% equipped vehicles

Table 1 describes that both ACC-controller improve the traffic flow. Surprisingly the ACC-system 1 shows a decrease of the average speed (deterioration 13%). This controller is designed to regulate the target distance with minimal deviations and short time lags, to improve traffic-flow and was optimised in a 'two-vehicle-following-situation' without consideration of a complex traffic situation. Because of the high traffic density in the simulated urban scenario the controller characteristic leads to overreacting and therefore oscillation of the vehicle-platoons. As a result the in all very high traffic flow locally collapses. The more smooth controlling ACC-concept 2 improves both traffic flow and average speed and keeps the traffic in stable condition.

### 3.4 Optimising through intelligent sets of traffic lights

A further possibility to improve the flow of traffic in suburban areas is the introduction of intelligent traffic lights. Such systems only change to red for the main traffic direction when

the number of waiting vehicles in the subordinate road exceeds a certain number or when the waiting time for these vehicles becomes unjustifiably long.

The evaluation of this optimising measure is carried out in the suburban area near the city of Aachen. Originally, the three successive sets of lights are phased at fixed times. The traffic lights are sequenced to allow no more than 1300 vehicles per hour to pass. The average duration of the red signal for the main traffic direction is 32 seconds. During the observation period a maximum of 8 vehicles turned into the observation area from the subordinate roads. Hence follows a maximum temporal demand of 16 seconds for the vehicles turning into the main road. The traffic light on the main road then shows a red signal even though all the vehicles from the subordinate road have passed already.

The introduction of intelligent traffic lights assures that the signals on the main road only change to red for as long as there is traffic from subordinate roads. Therefore the average duration of the red signal on the main road can be reduced from 32 to 15 seconds. Figure 11 represents the with PELOPS simulated improvements of throughput and travel duration resulting from this.

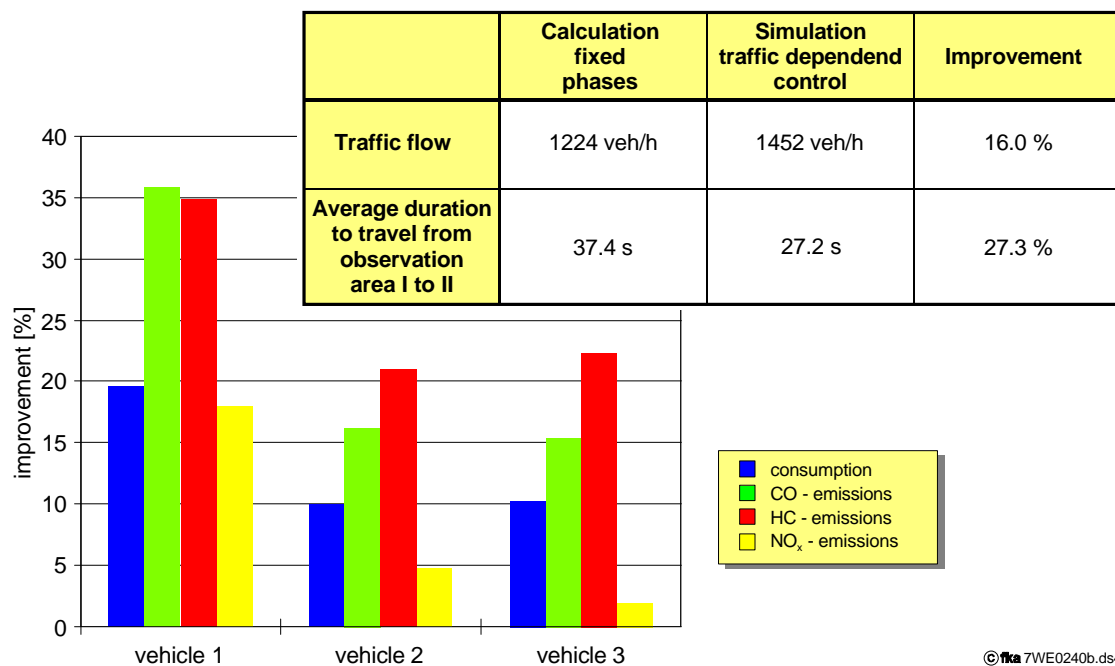


Figure 11: Improvement of throughput and travel duration through the introduction of intelligent traffic light systems

The small percentage of red signal phases at traffic lights on the main roads makes the flow of traffic generally smoother. This results in a considerable reduction of fuel consumption and emissions (Fig. 11). This can be shown for three representative vehicles. The extremely great improvements for vehicle 1 arise from the fact that this vehicle could pass through the observation area at a nearly constant speed during the simulation of intelligently sequenced lights. In the basic scenario with fixed traffic light phases, there was a high proportion of

halting and acceleration for this vehicle. Vehicle 1 therefore exemplifies the maximum possible reduction of fuel consumption (-20%) and emissions (up to -35%). Vehicles 2 and 3, on the other hand, represent the typical potential for reduction. Fuel consumption is cut down by approx. 10% and emissions are reduced by approx. 2% for NOX, by 15% for CO and by 20% for HC.

#### 4 Analysis of new Transportation Systems

The traffic on German motorways is heavily influenced by the amount of commercial vehicles. The speed and therefore the possible traffic throughput of commercial vehicles is by law limited to 80 km/h. By comparison, the share of passenger cars in the traffic does not have any or distinctly higher speed limits, resulting in high speed differences, particularly on two-lane motorways. Due to this situation lane-changing trucks do often cause local traffic collapses in the traffic flow on motorways under higher traffic density. Altogether does the average speed go down with a rising share of commercial vehicles.

Consequently, for an increase of the traffic volume on motorways two starting points arise:

1. Raise of truck speed
2. Raise of the maximum load and the transport volume

A very great potential for the improvement of traffic flow lies in the raise of the allowed top speed of commercial vehicles to 100 km/h. With trucks of the latest generation this is already possible due to modern drive-train-, braking- and chassis-technologies. If the maximum load and the transport volume are increased at the same time, the share of commercial vehicles in the overall traffic can be significantly reduced with an unchanging transportation mass (because of the less needed traffic space). By increasing the number of axles it can be furthermore be ensured that the stress on the road surface corresponds to or even remains under the one of conventional trucks.



Figure 12: Road Train - example

With the present vehicle technology it is possible to describe such extra long trucks („road trains“, figure 12). The longitudinal arrangement of drive-train and braking system can be realised as well as the stabilisation of the faster and extra long train or vehicle combination. New engines, disc brakes and new vehicle electronics, such as adaptive cruise control (ACC) or regulation of driving dynamics guarantee safety and a simultaneous increase of economic efficiency.

Apart from the technical practicability of the presented road-train concept it has to be ensured that the boundary conditions of the European road traffic are taken into consideration. For example, the driveability of entrance ramps has to be possible with the road train. Thereof results a corresponding dimensioning concerning the space demands of the road-train while cornering (e. g. by an additional steering system at the semi-trailer). Furthermore, the climbing ability has to be adjusted to European conditions.

The ika has investigated the influence of a road train concept for speed-100 on the traffic throughput, fuel consumption and the driving characteristics. The effects on longitudinal dynamics and traffic flow were analysed with the help of ika's own simulation system PELOPS. A truck, equipped with a 380 PS engine of the newest technology was simulated. The drive-train was dimensioned for a total weight of 40 t. By a hitched trailer a road train is realised and the payload is heightened from 24 t to altogether 48 t.

The first investigation step comprised an analysis of the influence of increased speed and maximum load on the fuel consumption. This was followed by an investigation of the influence of Road-Train-speed-100 on the traffic flow on a two-lane motorway. The simulations concerning fuel consumption were carried out on a part of the circuit of the German magazine 'lastauto-und-omnibus', possessing a maximum climb of 4%. Hereof result rather disadvantageous conditions for the operation of a commercial vehicle with a maximum speed of 100 km/h and increased maximum load. The basic vehicle with 40 t total weight consumes for this test circuit 40,5 l/100km. Is the maximum speed increased to 100 km/h, the fuel consumption is raised about 5%. With a simultaneous increase of the total weight to 72 t (road-train) the vehicle now needs 47,5 l/100km. These are hence 0,66 l per ton and 100 km of the speed-100-road-train as against 1,01l per ton and 100 km of the speed-80-basic vehicle. Despite of the demanding course with a high climbing percentage this signifies a fuel reduction of more than 34% concerning the total weight.

The effects on the traffic flow were simulated with PELOPS by means of a two-lane motorway for a middle and a high traffic volume. In both cases the Truck-share in the total traffic was 25%. Starting point of the investigation was a speed limit for Trucks of 80 km/h. Is the allowed maximum speed is raised to 100 km/h for all commercial vehicles, the average speed of the whole traffic with a middle traffic volume increases about 10% to approximately 120 km/h. With a high traffic volume the expected increase of 14% is even clearer (Fig. 13).

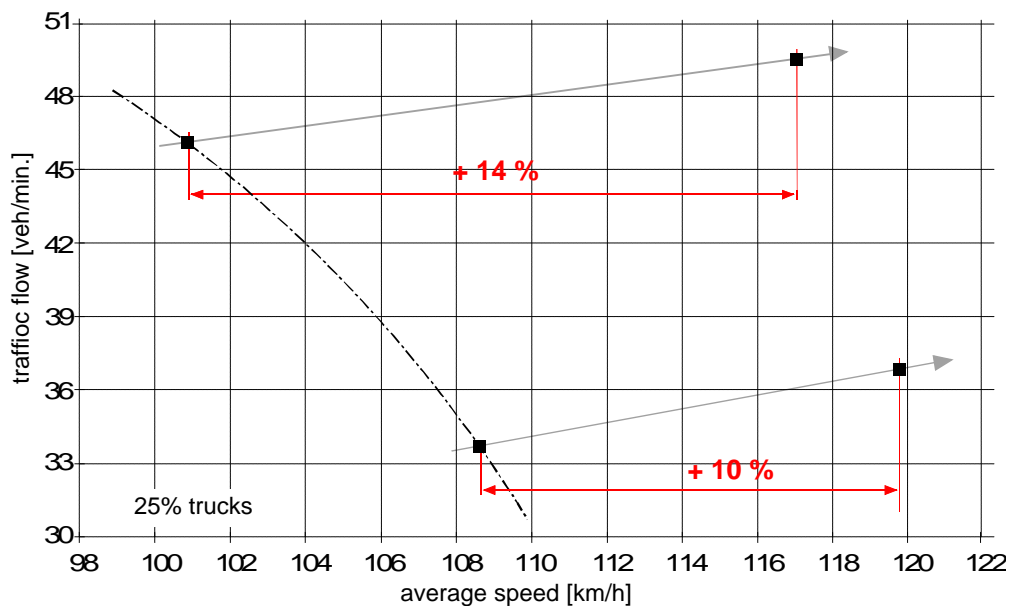


Figure 13: Speed and traffic flow improvement

As summary of these first analyses concerning Truck-speed-100 and use of road trains it can be observed that significant improvements are to be expected for the traffic flow as well as for the fuel consumption of the commercial vehicles. How exactly these improvements are to be quantified has to be clarified in a sequel investigation. In particular, the following criteria have to be taken into account:

- Conception of an optimised vehicle for speed 100 and increased maximum load
- Integration of electronic systems such as vehicle dynamics regulations or ACC into the investigation
- Analysis of different throughput rates of the commercial traffic with speed-100-Trucks and road trains
- Extended investigation of fuel consumption and emission of the single vehicles as well as of the whole traffic

## 5 Conclusion

The simulation of highway and urban traffic with consideration of driver behaviour, vehicle- and traffic-technology needs new approaches like PELOPS. It is shown that PELOPS is a powerful simulation tool for the investigation of intelligent traffic- and vehicle- systems. It is shown with the new simulation approach, what benefits different technologies bring to the general traffic situation. These improvements are related to higher traffic flow, more traffic safety and to a decrease in fuel consumption and emissions. It is demonstrated that

systems like ACC must not only be optimised in isolated 'two-vehicle-situations', but have to be investigated under realistic traffic conditions.

The idea of PELOPS to combine high detailed vehicle- and traffic technical models makes the analysis of new transportation technologies like high speed road-trains possible. The investigation of Truck-speed-100 and use of road trains observed that significant improvements are to be expected for the traffic flow as well as for the fuel consumption of the commercial vehicles.

Altogether it can be said that the introduction of new vehicle and traffic technologies contains an essential potential for improvements for traffic-specific characteristics as well as for fuel consumption and emissions.

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## 9. PELOPS Web-Site

<http://www.pelops.de>

**7 Abbreviations**

ACC Adaptive Cruise Control

DRIVE Dedicated Road Infrastructure and VEhicle Systems

MoTiV Mobilitaet und Transport im intermodalen Verkehr (Mobility and Transport in intermodal Traffic)

PELOPS Program for the dEvelopment of Longitudinal micrOscopic traffic Processes in a Systemrelevant environment

PROMETHEUS PROgraM for a European Traffic with Highest Efficiency and Unprecedented Safety