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Analysis of Advanced Autonomous and Infrastructure Based Drivetrain Control Systems with Minimized Emissions and Optimized Driving Comfort

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ABSTRACT

This paper will first describe the project FORFAHRT. The aim of FORFAHRT is the identification and analysis of improved low-emission drivetrain structures for integration into a driver assistance system. Part of the assessment during the project will be DI-spark-ignition engines, integrated starter alternator systems as well as different transmission concepts such as CVT-transmissions or automated manual transmissions. The analysis focuses on “conventional“ drivetrain components, not on hybrid or electric propulsion. The analysis is done with the sub-microscopic traffic simulation program PELOPS [5], which was developed at the ‘Institut fuer Kraftfahrwesen Aachen’ in co-operation with the BMW AG. PELOPS models the fundamental elements of traffic -namely route, environment, driver and vehicle- with highest accuracy. The second part of the paper gives first results of the project work. The achievable reduction in fuel consumption of an advanced vehicle control system which integrates traffic data and optimized drivetrain structure is finally described.

INTRODUCTION

For a minimization of emissions of road traffic, today mostly two approaches are followed: By means of comprehensive technical measures the pollutant emissions of the engine are further reduced on the one hand and on the other hand driving resistances effecting vehicles are lowered, e.g. by lightweight construction. Apart from purely technical optimization measures a significant potential for reducing emissions lies in the adjustment of vehicle operation and the driver’s way of driving to the respective traffic situation.

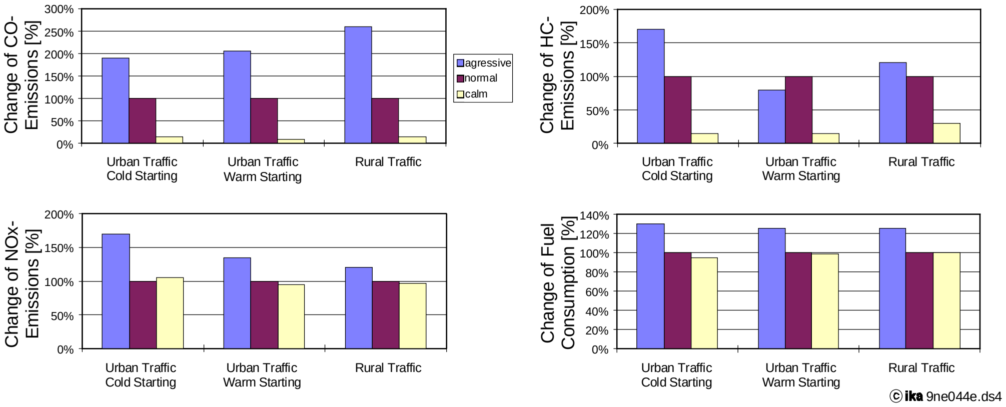

Figure 1. Influence of driving style on pollutant emission of an upper middle class vehicle with Euro 2-engine [6]

For an analysis of this potential the Institut fuer Kraftfahrwesen Aachen (ika) handles the project FORFAHRT on behalf of the German Ministry for Education and Research. Aim of FORFAHRT is the development of a vehicle concept that enables a considerable emission minimization by a forward-looking and therefore smooth way of driving over the short or medium term.

STATUS OF RESEARCH, EXAMPLES

By this calm driving style emission reductions (for CO2, air pollutants and noise) are possible that could by far exceed today's predictable technical reduction potential [4]. Figure 1 shows this fact by the example of comparative drives with upper middle class vehicles that are equipped with an Otto engine of the emission class Euro 2.

Other sources confirm the above named investigation. For example in [1] is presented that, in respect to the test-procedure, consumption minimization potentials can be achieved of approximately 10% by the vehicle's weight, 20% by the engine and 10% by the drivetrain, without limitation of the vehicle's performance. In contrast to this, the driver's influence amounts to a reduction of 25% on the average with existing automotive technique. For this investigation driving courses with the same average speed on a given stretch profile were evaluated.

Similarly big effects can also be achieved with non-automotive technical measures from the field of traffic engineering. In this context to be named are particularly traffic management systems or in inner-city traffic- optimized traffic light control. As example for the effects of traffic management systems the variable message signs on the highway A 9 in the north of Munich can be named. On this stretch changing traffic signs for accident reduction were installed that enable for example a traffic-depending transmission of speed limits or traffic jam warnings. A side effect of the introduction of this line influencing facility lies in a reduction of pollutant emissions and fuel consumption on this road section [3]. The emission reduction, represented in the following figure, is most of all due to a reduction of the Stop&Go share of approximately 90% and to a reduction of the speed share of 0-30 km/h in favor of higher speeds.

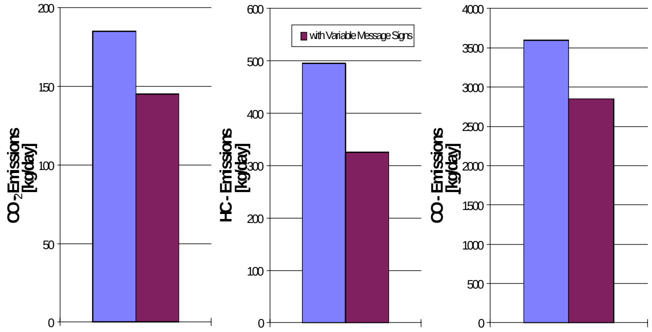

Figure 2. Emissions with and without variable message signs on the highway A9 (Munic, Frankfurt Ring/ intersection Neufahrn) between 6 and 10 o'clock a.m. [3]

In urban areas, comparable emission reductions can be achieved by means of throughput-optimized control of traffic lights. Through simulation this could be proofed for a suburban area of Aachen by the Institut fuer Kraftfahrwesen Aachen [2]:

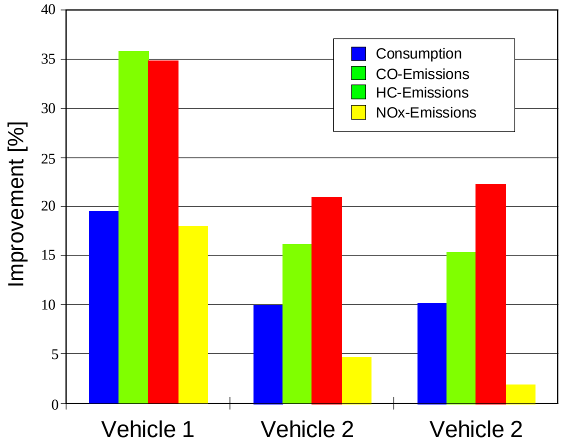

Figure 3. Improvement of fuel consumption and emissions by employment of optimized traffic light control in Aachen Lichtenbusch [LUD98]

Vehicles 2 and 3 in Fig. 3 indicate about the average achievable saving, whereas vehicle 1 shows the optimal reduction potential.

An even and therefore emission-reducing traffic can thus be achieved by so-called traffic management facilities or by an assisting system installed in the vehicle. In case of the collective influencing of traffic flow, the reduction of emissions represents today only a minor motivation apart from road capacity and increase of traffic safety, which actual effect on immission reduction is heavily discussed [4]. Furthermore, traffic influencing facilities are connected with high investments and cannot be installed at every stretch section (particular in urban traffic).

VEHICLE MANAGEMENT AND DRIVER ASSISTANCE

On part of technical measures for consumption and emission reduction a significant reduction of driving resistances could be achieved in recent years by lowering air resistance as well as by reduction of roll resistance. However, this development was partly neutralized by the simultaneous increase of vehicle weight. A significant reduction of weight and thereby caused reduction of pollutant emissions could up-to-now only be rarely realized in series vehicles. The emission of vehicles are therefore mainly reduced by an improvement of the engine and a more efficient catalyst after treatment of exhaust gas. A combination of these measures with the use of renewable and low-carbon energy carrier promises a further reduction potential for vehicle emissions in future.

The measure groups „Traffic Flow Manipulation“ and „Reduction of Pollutant Engine Emission“ are however connected with high development expenses and costs as well as with significant requirements at the infrastructure. Clear effects for the minimization of traffic emissions by these measures are from today’s point of view to be expected over the medium or long term. Aim of the presented project lies therefore in conception, analysis and later realization of technologies from two complementary measure groups, in order to reach a significant reduction of pollutant emission already in a few years (Fig. 4).

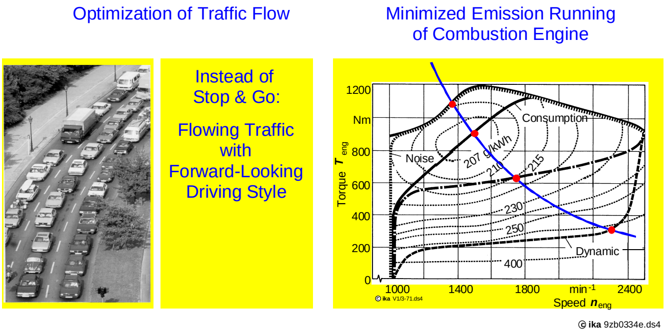

Figure 4. Approach of „FORFAHRT“

Both measure groups can thereby achieve their reduction potential by combination of adjusted single components and base on existing (that is available today or in the next years) technology. Optimization of driving operation should thereby be realized by a particularly forward-looking driving style of the vehicle itself with a driving course as even as possible. The emission-minimized operation of combustion engines can follow by selection of the respectively optimal operational point.

The availability of a sufficient information amount concerning the current traffic situation in direct environment of the vehicle and on the route ahead represents an essential precondition. The information can then be converted by suitable drivetrain elements (such as, e.g., a CVT-transmission) and an adjusted driver assistance system (e.g. an extended ACC-controller [7]).

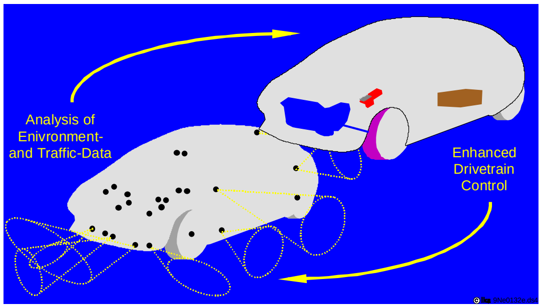

Figure 5. Driver assistance for emission-optimized driving style

In a first step the necessary information about the local traffic situation (starting from stop & go up to „free driving“) is determined by the driver assistance system itself. Such an approach does however only reach it’s full performance capacity, if a forward-looking driving style is enabled, based on centrally registered traffic data.

In the course of the project it is analyzed, how the share of emission-unfavorable acceleration phases can be reduced by employment of innovative drivetrain technique and traffic information, without simultaneously deteriorating stretch throughput and travel time of the overall traffic. Thereby it is of particular interest, whether consumption and emissions of the non-equipped vehicles are positively influenced by an reduction of the driving course dynamics of the equipped vehicles.

The technologies to be analyzed for the processing of traffic situation information can be basically divided into two groups:

- Vehicle-autonomous systems register all relevant data in the vehicle itself
- Infrastructure-based systems get their information from a suitable communication channel of surrounding vehicles or control devices.

Completely vehicle-autonomous systems (e.g. Stop&Go control on the basis of ACC) possess the advantage that in combination with drivetrain systems such as CVT-drives and integrated starter-alternator systems they can already soon be introduced in series vehicles. Furthermore, they enable an engine control in a wide operation range. Over the medium term the emission minimization potential of these systems can still be greatly increased by processing of infrastructure data (e.g. traffic light approaching control for controlled engine starting / stopping, neutral position etc.).

Table 1 summarizes examples of the relevant technologies to be regarded for evaluation of traffic flow and therewith combinable drivetrain technologies, their classification to the group vehicle-autonomous systems as well as their availability. These technologies serve as basis for conception and analysis of strategies for an emission-minimized vehicle concept. First results are presented in this paper.

Table 1. Examples for relevant technologies

Technologie	*vehicle-autonomous*	*today available*	*midterm available*
ACC	√	√	
Adaptive Accelerator Pedal	(√)	(√)	√
GPS	(√)	√	
Digital Maps with traffic signs	(√)	(√)	√
Automatic Gearbox	√	√	
Automated Manual Gearbox	√	√	
CVT	√	(√)	√
ISAD	√		√
Traffic Data	(√)		√
Stop&Go Detection	√		√
Communication			√
Junction Management			√

DRIVE TRAIN CONCEPT

Starting point of the analyzes represents a selection of the drivetrain technologies to be investigated. For an upper middle-class vehicle suitable latest EURO 3 and EURO 4 engines are to be selected and to be reproduced in simulation. The focal point lies thereby on direct injection engines. If the respective engine specifications are not available, it is relied on an estimation of consumption and emission characteristics, being derived from current publications.

Aim of the drivetrain control lies in an optimal and emission-reducing adjustment of engine operational point and drive transmission to the current driving situation and speed. For controlling the emission-favorable engine operational point the respective transmission must be adjustable, if possible. In case of a conventional transmission this can lead to an extremely high amount of gears. Additionally, the task requires an automation of the drivetrain, in order to relief the driver of necessary and frequent transmission changes. The requirement range is at first only fulfilled by CVT-transmissions. This kind of transmission enables a free choice of the gear ratio with simultaneously good effectiveness. The following figure compares these advantages of CVT-drives with the properties of conventional step automates and 5-gear-manual transmissions.

Basically, the CVT-transmission seems to be best suited for emission-reducing drivetrains. However, it can still not be predicted, whether the expected consumption savings and expected low costs of this transmission can be realized in praxis. Therefore, also automatic transmissions and particularly automated manual transmissions must be included in an analysis of the drivetrain conception.

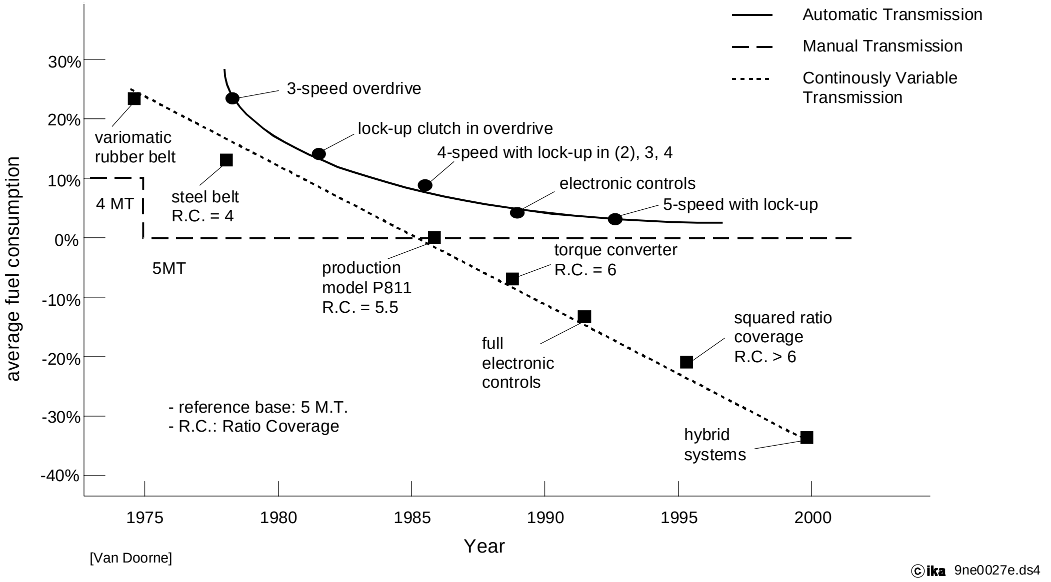

Figure 6. Principal fuel-minimization potentials of different transmission types [Van Doorne]

If a complete decoupling of engine operational point and driving situation has to be achieved, the above named transmission can be combined with an integrated starter-alternator-damper (ISAD). Such a system is installed between engine and transmission. The employed ISAD electric engine assumes the function of generator and starter. At the same time the system can be used for damping drivetrain vibrations. Due to the capacity of the electric machine the engine can be started in a nil of a time. Thus, a start-stop-automatic is easily realizable, without loss of driving comfort. A further field of employment of ISAD is the lowering of the neutral RPM and therefore a reduction of fuel consumption and pollutant emission in short periods of still stand, in which a complete stop of the engine is unfavorable for emission minimization (e.g. due to lower catalyst temperature). Additionally with this system, the engine operation point can be displaced to emission favorable ranges by shortly generating an additional torque by the electric engine. The electrical power, which is only needed in a short period, can be won back in braking phases so that there is no need for a high-performance battery, which is necessary for hybrid drives.

TRAFFIC INFORMATION AND DRIVE TRAIN CONTROL

For the capacity of the driver assistance system, infrastructure data, integrated into the strategies for emission-minimal operation of the vehicle, are of particular importance. By means of infrastructure information the vehicle for example can react early to traffic jams or traffic lights on the route ahead. For this end, comprehensive data is necessary that is not available today. Thus, a communication between a traffic light control and an approaching vehicle has to be made possible that eventually will enable an approach with switched-off motor in case of red light. Furthermore, the functionality of an extended vehicle-navigation system has to be integrated into simulation, in order to register detailed information concerning stretch (f.i. incline, curves or traffic signs) on the route ahead. In particular, data about the traffic situation ahead („dynamic navigation") should be taken into consideration.

Aim of this work package is the analysis of traffic data that is absolutely necessary for an effective operation of the drivetrain control. Furthermore, it has to be presented, how high the emission minimization potential of the processing of this additional traffic data is.

A further goal lies in the preparation of an optimal control strategy for the drivetrain and therefore for a selection of the optimal engine operational point by means of an analysis of the traffic data. On the other hand a driving strategy has to be developed that enables an even and therefore emission-optimal way of driving, without disturbing traffic flow. The following figure shows exemplary a typical traffic situation to be evaluated by the driver assistance system. Analysis of such traffic situations need a suitable tool: the vehicle oriented traffic simulator PELOPS.

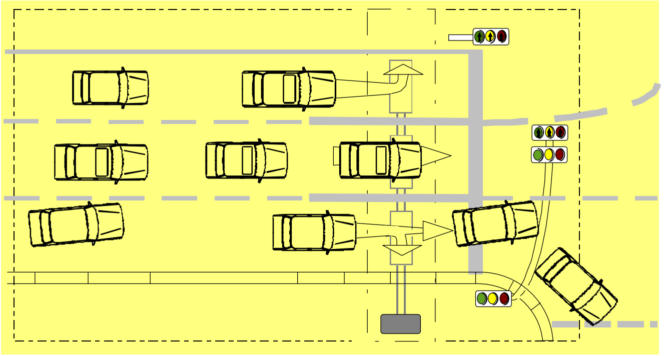

Figure 7. Driving strategy and evaluation of the traffic situation

THE SIMULATION TOOL PELOPS [5]

The idea of PELOPS is a combination of highly detailed sub-microscopic vehicle- and microscopic traffic technical models, that permits investigations concerning the longitudinal dynamics of vehicles as well as an analysis of the course of traffic [10]. 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 computer capacity was significantly optimised during last years. Without this capacity the required degree of detail with a simultaneous consideration of all influencing factors would be unthinkable.

PELOPS is orientated towards the fundamental elements of traffic, namely route and environment, driver and vehicle (Fig. 8). The route model is based on the description 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 the number of lanes with their 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 initial conditions of the traffic situation are given by the number of vehicles driving on a stretch of road with a defined length (traffic density) as well as from their starting speeds and their distances (traffic flow). To simulate 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. With 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.

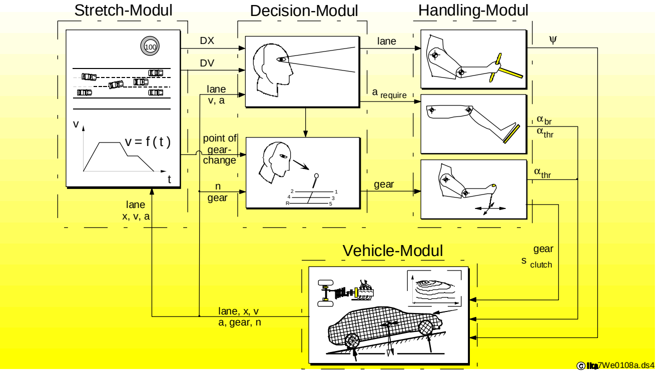

Figure 8. The simulation system PELOPS

VEHICLE MODEL – The vehicle model is based on the 'cause- and effect-method' [8], which means that the order of calculation is based on the operational point of the engine (speed of rotation rate and load) and continuous over the clutch, transmission and differential to the rotor gears where the tractive- and resistance powers are balanced. (Fig. 10) The operational point can be changed by altering the load (cause), that is adjusted by the driver and leads to a change in power and therefore to a change of the speed of rotation rate (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.

The implemented transmission designs are a conventional manual- and an automatic transmission model with a hydrodynamic converter as well as CVT drivetrains. 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 (adaptive cruise control, ABS, etc.) possible.

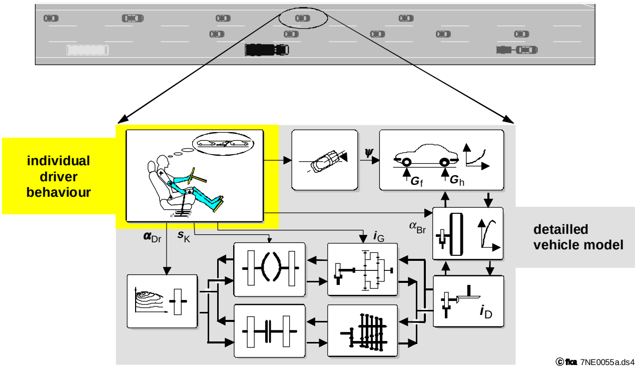

Figure 9. PELOPS vehicle model

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. The driving intention consists of acceleration, choice of lane and gear and a strategy-level for reacting to intersections, traffic-lights etc. To ascertain the driving intention, PELOPS works with a psycho-physical 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 pedals 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 the lateral dynamic is neglected. 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.

Following Behaviour – The basis of the driver model is a psycho-physical follow the leader model. It has been introduced 1974 by Wiedemann [12]. For the application in PELOPS this model had to be developed further and extended substantially [9] [11] [2]. 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.

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 as a range of visibility or a reaction to surrounding vehicles have to be implemented. Fig. 11 shows an example for a traffic situation which is analysed by the „tactical driver model".

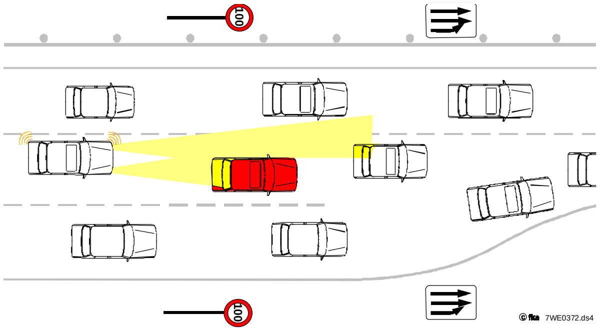

Figure 10. Detection of traffic situation

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. The next figure shows the basic principle of the modelled lane-changing decision.

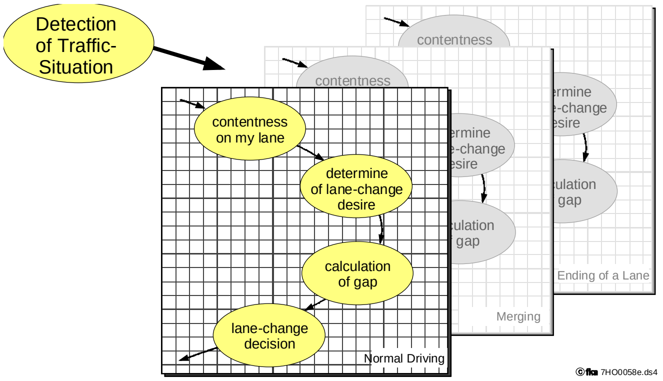

Figure 11. Structure of lane-changing model

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 varying driver's behaviours. Depending on the driver's contentment on their current lane a desire for lane-changing is determined. If the gap on the neighbour-lane is large enough, the driver model will initiate a lane-change. The gap is depending on the differential speed between the vehicles and the driver's individual need for safety.

RESULTS

This section shows some first results of the here described project FORFAHRT. It focuses on the strategy development for driver assistance systems by analyzing the fuel consumption during acceleration as well as on the potential of different drivetrain structures. The section finally points out how a driver assistance system can reduce the consumption in traffic.

FUEL-CONSUMPTION AND ACCELERATION STRATEGY – The fuel consumption of a vehicle during an acceleration phase depends on their duration and the gear changing strategy.

Figure 12 shows the results of PELOPS simulations for an upper class vehicle with about 150 kW engine power (BMW 528i, automatic gearbox) and a middle class vehicle with about 55 kW engine power (MB A-Class 140, manual gearbox).

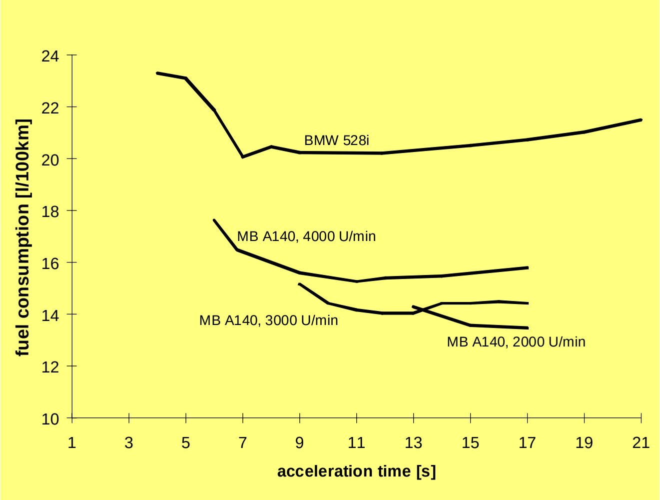

Figure 12. Finding the optimum between acceleration time and fuel consumption

For both vehicles an optimum can be found between acceleration time and fuel consumption. Depending on the driver's wish for acceleration or depending on the actual traffic situation (see figure 7) the best strategy must be chosen. If the surrounding traffic allows only a slow acceleration of the vehicle (e.g. in an traffic jam during stop & go) the gear changing strategy can be adjusted to this and less consumption is possible (see figure 12, MB A 140, gear changing at 2000 1/min engine speed). A conventional automatic gearbox already changes gears depending on the position of the throttle and therefore reacts to the driver's wish for acceleration. But with taking the traffic situation ahead into consideration (e.g. by using the headway sensor of an ACC-system) and estimating the acceleration time for this situation the fuel saving potential may be further increased.

FUEL CONSUMPTION AND DRIVETRAIN CONCEPT –

To compare the influence of different drivetrain structures on the fuel consumption four different transmissions were simulated with PELOPS.

1. conventional 5-speed automatic gearbox
2. conventional 5-speed manual gearbox
3. CVT-transmission with torque converter
4. CVT-transmission with clutch (like presented by Audi for series introduction in the A6

Each drivetrain was simulated in the same upper class vehicle (see figure 12) with the same engine, same weight, etc. Only the transmission was changed, so that the results can be compared directly and it is possible to see only the effect of the changed transmission. The efficiency map of the CVT drivetrain has to be estimated and is on the same level as the efficiency map of the conventional automatic gearbox.

To get a representative picture of realistic traffic situations two measured driving courses in city traffic and one driving course on a German highway were simulated with PELOPS for each drivetrain configuration. Finally the standardized FTP75 driving course was simulated.

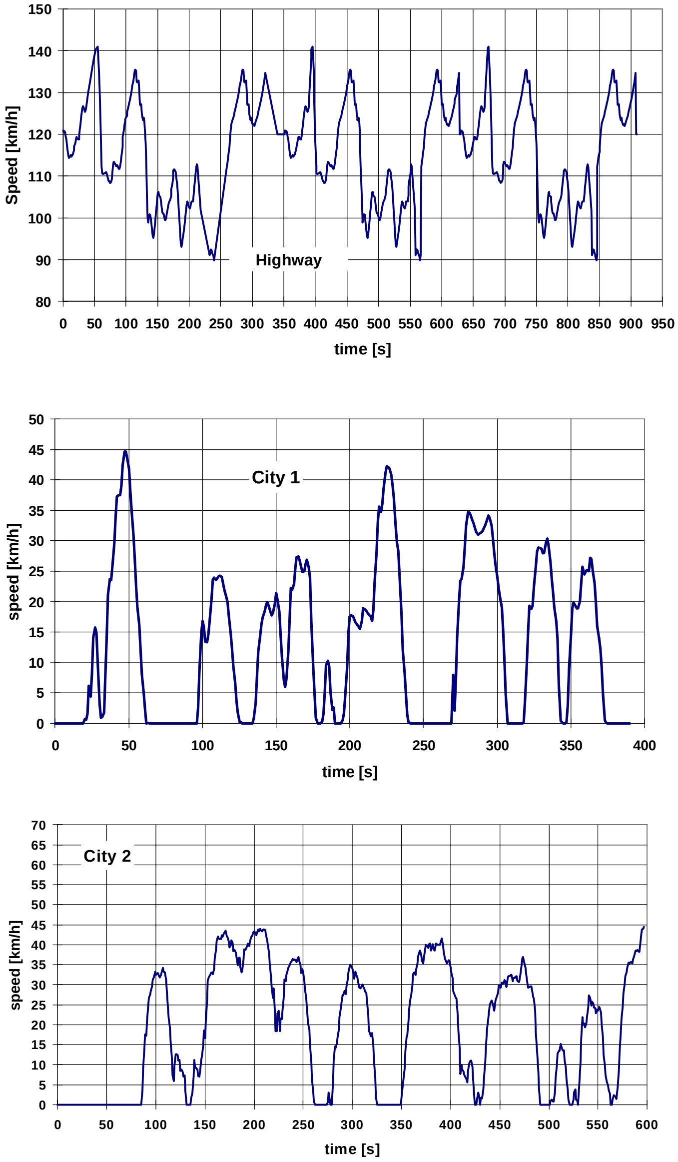

Figure 13. Simulated driving courses, sections

The following table shows the simulation results in comparison to the conventional 5-speed automatic gearbox.

consumption compared to automatic transmission	manual gearbox	CVT with torque converter	CVT with clutch
Highway	-1.5 %	+5.3 %	-14.7 %
City 1	+2.0 %	+0.7 %	-9.5 %
City 2	-0.5 %	0.0%	-12.4 %
FTP 75	+3.4%	-1.8 %	-20.0 %

Figure 14.Fuel Consumption of the simulated drivetrain concepts compared to the automatic transmission

The simulation results of the CVT transmission with clutch represents distinctly the fuel saving potential of new drivetrain technologies in the analyzed traffic situations.

FUEL-CONSUMPTION AND DRIVER ASSISTANCE IN URBAN AREAS – In the third part of the here described analysis the focal point lies on the effect of an ACC-system [5] on the fuel consumption in “real” (here simulated with PELOPS) traffic. With the investigated scenarios the effect in urban traffic shall be presented here. A highly frequented, traffic light controlled and one-lane access road in the Aachen suburban area served as investigation ground. Here, measuring was collected in the morning rush hour, in order to register the traffic in terms of macroscopic data (average speed and traffic density, relating to overall traffic) as well as of microscopic data (frequency distribution of distances and velocities, relating to single vehicles).

On the basis of this data a simulation with PELOPS was arranged. The parameters were calibrated so that the measured situation could be reproduced. In the following this "Basis-Simulation" serves as reference for simulations with ACC. Different equipment degrees were analysed for the effect of the ACC, in order to demonstrate the effects in different time horizons. The equipment degrees were set to 5%, and 40%. Additionally, a simulation with 100% equipment - meaning that only ACC-vehicles were simulated - was carried out for the assessment of the ACC's potential.

The real effect of an ACC-system on the fuel consumption strongly depends on the behavior of the driver. A very fuel efficient driver may not be surpassed be the assistant system. The next figure shows this very clearly by comparing the same driver-vehicle-combinations with and without ACC in the above described scenarios. The difference in fuel consumption is plotted for the three different equipment rates with the driver assistance system.

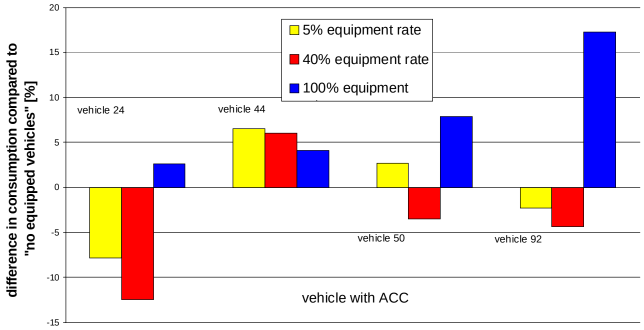

Figure 15. Fuel consumption of ACC vehicles [13]

The driver assistance system “smoothens” the traffic, strong accelerations are prevented by the system so that a positive effect on the fuel consumption of vehicles, which are not equipped with ACC can be shown.

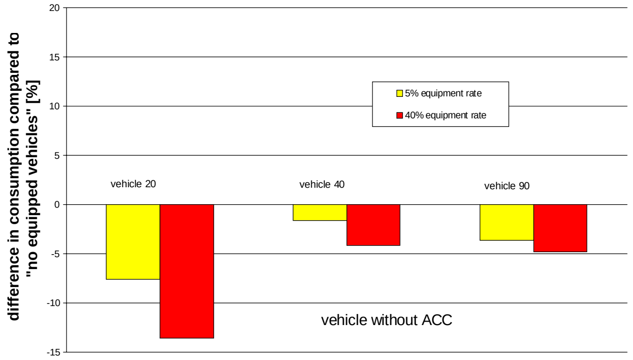

Figure 16. Fuel consumption of vehicles not equipped with ACC [13]

CONCLUSION AND OUTLOOK

The paper described the course of the project FORFAHRT. The aim of FORFAHRT is the identification and analysis of improved low-emission drivetrain structures for integration into a driver assistance system. The Institut fuer Kraftfahrwesen Aachen (ika) handles the project FORFAHRT on behalf of the German Ministry for Education and Research.

The analysis focuses on “conventional“ drivetrain components, not on hybrid or electric propulsion. The analysis is done with the sub-microscopic traffic simulation program PELOPS [5], which was developed at the ‘Institut fuer Kraftfahrwesen Aachen’ in cooperation with the BMW AG.

The first results of FORFAHRT presented in this paper show the high fuel saving potential of optimized drivetrain structures using a CVT transmission. Combined with a driver assistance system like an advanced ACC-controller the fuel saving potential may be even increased.

The project FORFAHRT now starts into its main phase. Improved low-emission drivetrain structures for integration into a driver assistance system will be identified and analyzed. Part of the assessment will be DI-spark-ignition engines, integrated starter alternator systems as well as automated manual transmissions. The last phase of the project will then examine which amount of traffic data is necessary to realize a smooth traffic dependent driving style.

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