

Integrated Simulation of Traffic Demand, Traffic Flow, Traffic Emissions and Air Quality

presented by Dr. Martin Fellendorf at the
8th International Symposium on Transport and Air Pollution,
Graz, Austria, 1999



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Integrated Simulation of Traffic Demand, Traffic Flow, Traffic Emissions and Air Quality

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Abstract

This paper introduces the simulation software developed by the Group Research Department of the VOLKSWAGEN AG and the PTV system GmbH. Five separate models are integrated in one software suite to cover traffic demand, route choice, traffic flow, traffic-induced emissions and air quality. The traffic demand model follows a behaviour-oriented, disaggregated approach. The dynamic route choice is calculated by an iterated simulation of the entire day. Each individual vehicle travels through the road network using a microscopic traffic flow model. Fuel consumption and exhaust gas emissions of all vehicles in the network are determined based on dynamic characteristics of the TÜV Rheinland. A new microscopic approach is presented which includes cold start and warm-up induced extra emissions. It contains a thermodynamic part model for engine and catalytic converter improving accuracy in comparison to previously known calculation methods, The air quality is calculated with a microscopic flow and dispersion model considering the 3-D structure of built-up-areas. Typical applications of this simulation software extend from traffic and air quality-oriented assessment of isolated intersections up to optimising the entire road network of cities.

1 INTRODUCTION

Modelling traffic-induced emissions and the resulting air quality is gaining increasing importance in urban areas. The entire sequence starting with the mobility of the inhabitants up

to the air quality can be simulated by a number of models: Disaggregated traffic demand models describe the daily trip pattern of individual persons. Microscopic route choice and traffic flow models can be viewed as a model of motorist' choice of path from origin to destination. Emission models calculate the exhaust gas amount arising from the traffic flow of the motorised traffic, from which the resulting air quality is then determined with a dispersion calculation.

It is state of the art to use such models separately of each other. Typically the results of one model are used as input for the next model. Two problems arise in this case:

- Normally information losses due to aggregation occur in the transition between the models and
- when simulating state changes, feedback across several models is not possible.

In the presented simulation software on the other hand, traffic demand, route choice, traffic flow, vehicle emissions and air quality are simulated over an entire day on the same microscopic model level (Kohoutek et al., 1999). In order to calculate the vehicle emissions the integration of these models leads to an important advantage supported by data of the thermal state of the engine and the catalytic converter on the base of the trip chain. Thus the cold start and warm-up induced extra emissions of all vehicles in the network can be calculated more accurately than would be possible by the lump sum addition of cold start supplements.

The simulation software is based on five models for traffic demand, route choice, traffic flow, emissions and air quality. The route choice model and the traffic flow model require the same input data with extensive iteration loops between both (Figure 1).

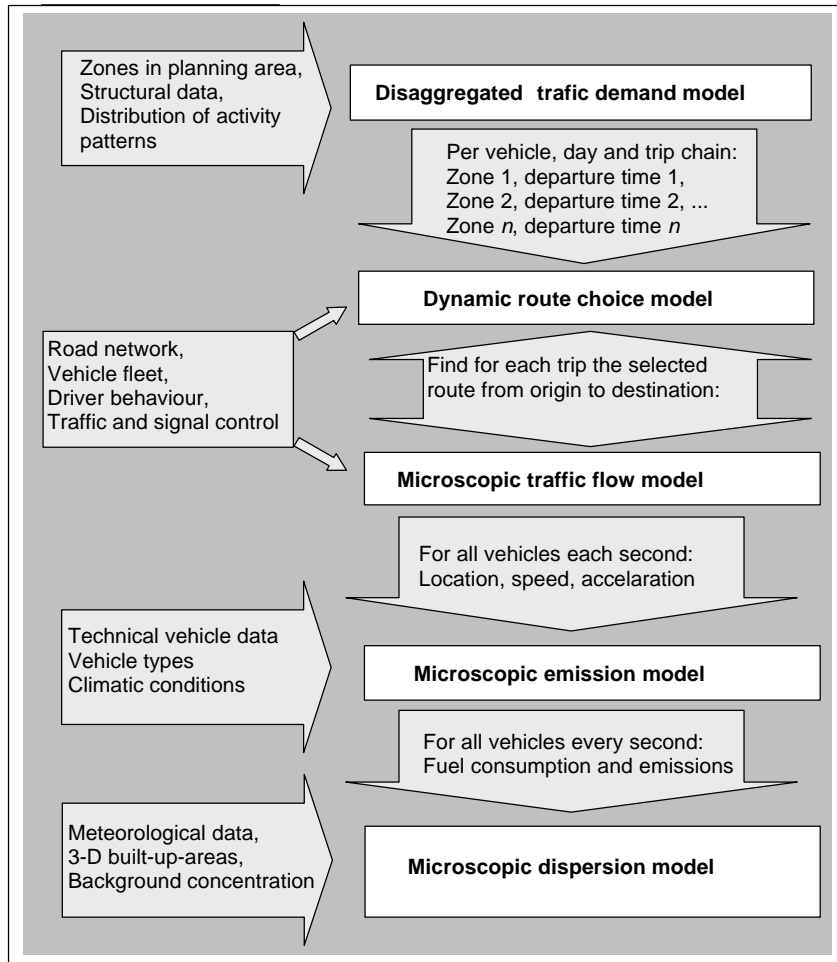


Figure 1: Data flow between the individual models within the simulation software

2 DESCRIPTION OF THE INTEGRATED INDIVIDUAL MODEL

2.1 Disaggregated traffic demand model

An adapted version of the VISEM model (Fellendorf et al. 1997) calculates the traffic demand. The demand model uses a disaggregated and behaviour-oriented approach. The population is classified into behaviourally homogeneous groups and their typical activity patterns are modelled.

The demand model includes :

- Traffic generation (from where (origin) are requests for zonal change ?),
- Traffic distribution (what are the destinations of these requests for a trip ?),

- Mode choice (what mode like car, bus, bike or foot is taken ?).

The traffic generation model calculates the traffic demand originating in one zone for a given period of time. In each zone the population is classified into so-called behaviourally homogeneous groups with the assumption of characteristic mobility behaviour. This mobility behaviour is represented by a distribution of typical activity chains (e.g. living – working – shopping – living).

The traffic distribution model calculates the directed traffic demand. The traffic proceeding from each zone is distributed over the suitable set of destinations. For each trip, being a result of the activity chains of each group, a mode to travel has to be chosen. Since we are concerned about traffic induced pollution, we will follow up only car traffic.

The result of the traffic demand calculation is the entire set of individual trip chains which take place within one day in the study area. One trip chain passed onto the following dynamic route choice model contains all single trips of one vehicle during this day with the information about departure time and destination zone which is important for the emission model.

2.2 Dynamic route choice model

The distribution of the traffic demand is called traffic assignment. In our model the assignment is done dynamically over time by an iterated application of the microscopic traffic flow model (see Section 2.3). The iteration is done in steps between 5 Minutes and 1 hour representing changes in route choice behaviour due to fluctuations in signal control and variations in congestion.

Trips start and end at a zone. A zone is an idealistic spacial area. Carparks represent the physical origin and destination point. Each zone has one or more carparks.

The set of links on the modelled road network between the starting and the ending carpark is called a route. The specific route chosen depends on the current travel times on each link which is effected by the departure time.

Based on travel time measurements of the preceding simulation, the fastest route between carparks is considered in each iteration. However, not all vehicles will drive on this route, but all routes between the two carparks which were already found in the preceding iterations will be used. All vehicles with the same origin-destination pair will be distributed on the set of suitable routes according to Kirchhoff's-law know from electrical physics. The fastest route will get the highest loading, but routes with similar travel times will receive nearly as high flows. The travel times on each road link are determined in during the previous iteration.

The sum of all route choice decisions leads to a dynamic assignment of the given traffic demand. The traffic loadings on each link converge after several iterations. Since no travel times are available in the first simulation run, the initial route search is based on link length. The principle of iterated simulations is illustrated in Figure 2.

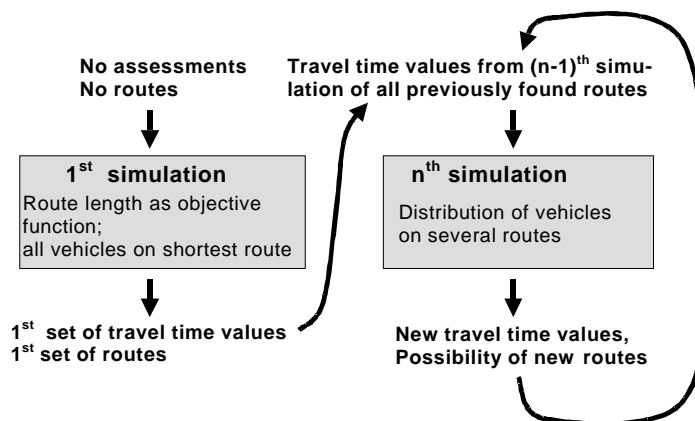


Figure 2: Principle of dynamic apportionment by iterated simulation

2.3 Microscopic traffic flow model

The traffic flow on the road network of the study area is simulated with a further development of VISSIM (Fellendorf et al. 1994), which models driver-vehicle-units. Individual driver behaviour is considered by using a psycho-physical car following and lane-changing model with distributions of perception thresholds. The driving behaviour is simulated in discrete time steps. A time step of one second is used for calculation over all models in the simulation software. However, to increase the modelling accuracy, a higher temporal resolution is can be used for the traffic flow model. The driving behaviour is subject to calibration with regard to the characteristics relevant for the emission calculation.

The traffic infrastructure is simulated in detail. Number of lanes, lane markings and geometry are superimposed on scaled layout maps. For public transport, stops are created on the road network as well as timetable information for buses and trams. Traffic regulations like priority rules, speed restrictions and signal control are simulated realistically. Since signal control is the most important measure for urban traffic management schemes various types of vehicle actuated signal control are available to extend or shorten green times depending on traffic demand.

2.4 Microscopic emission model

The microscopic emission model determines for each vehicle and in every second the traffic-induced emissions on the basis of exhaust gas emission maps of the TÜV Rheinland. In this case the method for calculating the passenger car emissions differs basically from the method of calculation for heavy commercial vehicles.

In the case of passenger cars, so-called dynamic consumption and emission maps on the basis of chasis dynamometer tests are produced. This method was already presented by Haghofer (1982), since then methodically improved and is also used for the calculation of the emission functions in Hassel et al. (1994). The associated emission values are read off each

second from the exhaust gas emission maps for each emission-relevant vehicle layer, depending upon the speed and acceleration known momentarily from the traffic flow model. The advantage of this method is that arbitrary movement patterns can be modelled. However, the predictive quality is moderate without additional further dynamic correction functions for individual driving cycles, see Section 2.4.1.

The emission maps of the heavy commercial vehicles are derived on the basis of stationary engine test bench examinations. The engine power required for overcoming the road resistances is calculated for each second for the speed curve known from the traffic flow model. The load condition in the engine map is determined for each second with the axle and transmission gear ratios in combination with a model which simulates the gear shifting behaviour of the driver. The associated emissions are determined by means of interpolation from the three closest measured values. Consumption and NO_x emissions can be displayed from the stationarily measured map even for dynamic cycles with a few percent deviation. For CO and HC there arise in part deviations of more than 50%, which, as also already mentioned for passenger cars, can be largely eliminated by an additional dynamic correction function, see Section 2.4.1.

2.4.1 Dynamic correction functions for calculating the exhaust gas emissions in the operating temperature condition

2.4.1.1 Passenger cars

In order to examine the possibilities of improving the accuracy of the emission calculation on the basis of the maps of the TÜV Rheinland by a dynamic correction, measurements were performed on the chassis dynamometer of the TU Graz on a total of 12 modern passenger cars with spark ignition and diesel engines. In this case apart from the FTP-75, NEDC and US highway cycles, 6 urban driving cycles for urban traffic were also measured.

In the examinations the differences between the measured and calculated emissions were examined by means of multiple regression analyses. Since with the given vehicle layer the speed curve in steps of one second should be used as sole input variable for the emission calculation, further analyses were limited to explanatory variables which can be derived from the speed curve (e.g. number of the changes from positive to negative speed gradients, idling portions, mean acceleration values, etc.).

The optimum correction functions were determined for each individual vehicle in the regression analyses. Certainly, these contain in part different variables for different vehicles. Therefore the variables which showed sufficient significance for most of the cars were determined. An average "dynamic correction function", which represents the difference between the measured emissions and the emissions calculated with the emission map, was formed with these variables. Figure 3 shows as an example the results for the HC emissions from the map calculation without and with the current state of the dynamic correction function in comparison with the measured values.

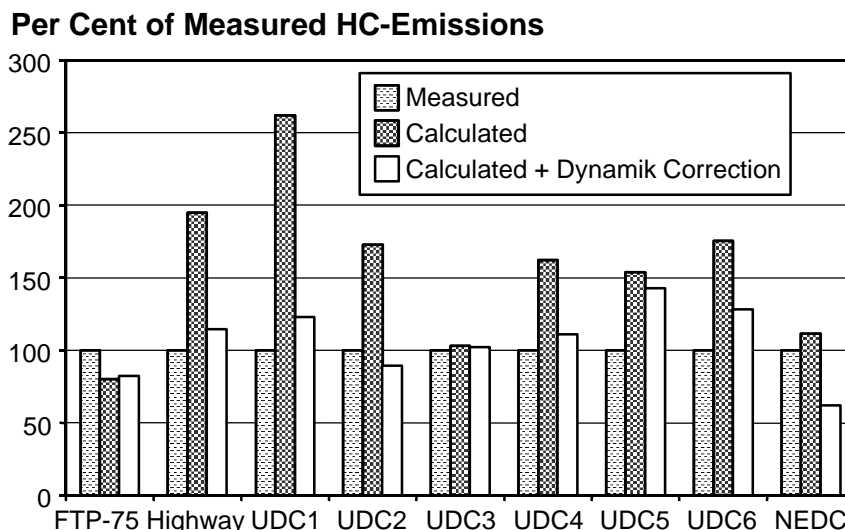


Figure 3: HC emissions from the map calculation without and with the dynamic correction function in comparison with the measured values for urban cycles and the FTP-75, NEDC and US highway cycles used for production of the map (spark ignition Gkat vehicle layer as from year of build 1994)

The dynamic correction leads in most cases to considerable improvements in the correspondence between measurement and calculation. Certainly, further investigations are necessary in order to be able to achieve even greater agreement.

2.4.1.2 Heavy commercial vehicles

Since only stationary engine maps are available for the heavy commercial vehicles, the variables to be derived from speed and torque curves were examined for their influence as explanatory variables in turn by means of multiple regression analyses (e.g. number of the changes from increasing to decreasing power requirement, the amplitudes of M_d , n and P_e , average positive engine power, etc.). The found "dynamic correction functions" improve noticeably the reproduction for dynamic cycles in all components. The correction functions are as expected different for different engine concepts (suction engine, exhaust gas turbocharger and exhaust gas turbocharger with charging air cooling).

The entire calculation method (road resistances, gear shifting model and emission calculation from the map) was checked by means of measurements on the truck chasis dynamometer and showed entirely good results. Figure 4 shows the comparison of measurement and model result for an urban cycle of a distributor truck.

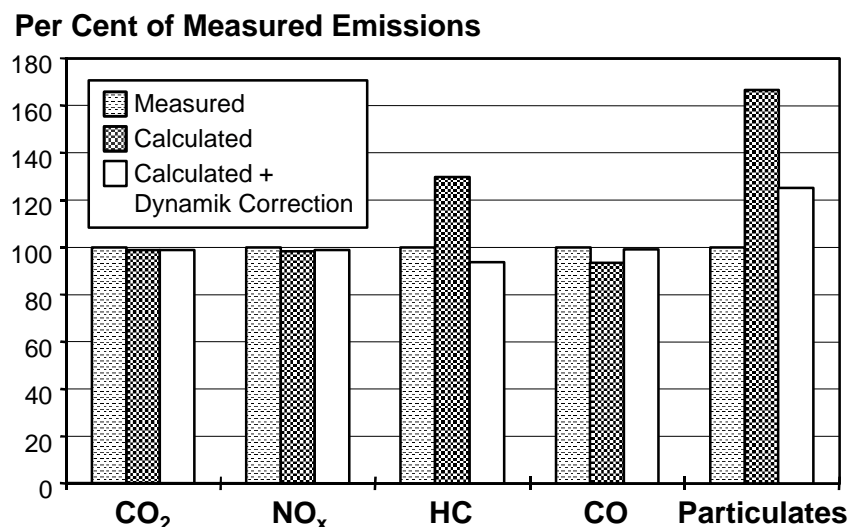


Figure 4: Comparison of measured emissions and emissions calculated with dynamic correction (Distributor truck, city cycle, fully loaded)

2.4.2 Calculation of the passenger car emissions in condition not at operating temperature

With the progressive use of constantly improved catalytic converters, which reduce the emissions in the operating temperature condition to a very low level, the accurate modelling of operationally induced extra emissions during the cold start and warm-up of the engine are gaining increasingly in significance. Previously the approach of the TÜV Rheinland (Hassel et al., 1994), which since then has been methodically improved (Sonnborn et al., 1997), was used mostly for calculating these emissions. However, this approach can be used only for a cold started engine (switch-off duration of the vehicle as a rule ≥ 8 hours).

In order to take into account both cold starts and starts below the operating temperature (shorter switch-off duration of the vehicle), a new methodical approach for calculating the passenger car emissions in the condition not at operating temperature was developed in the Volkswagen Group Research Department. This new method was derived from cold start investigations in the FTP-75 and NEDC under certification conditions (approx. 22 °C cold start temperature) and checked with a mobile exhaust gas measuring system in real road traffic. Spark ignition and diesel vehicles from current production were available as test vehicles.

Since the investigations on petrol driven vehicles were not yet completely concluded at the time of printing the manuscript, the method for calculating the extra emissions during the cold start and warm-up for diesel driven vehicles is presented and compared with the method of the TÜV Rheinland .

The new method of the TÜV Rheinland (Sonnborn et al., 1997) assumes that the operationally induced extra emissions ΔE after a cold start depend upon the heating up of the engine which is a function of the work done by the engine.

Approach of the TÜV Rheinland:

$$\dot{m}_{cold,i}(t) = \dot{m}_{warm,i}(t) + \Delta E_i \quad (\text{Equation 1})$$

with

$\dot{m}_{cold,i}(t)$ = exhaust gas emission of the cold engine [mg / s]
 $\dot{m}_{warm,i}(t)$ = exhaust gas emission of the warm engine [mg / s]
 ΔE_i = extra emission [mg / s] = $\Delta E_i = f(\text{Work}, i, T, FzKonzept)$
 T = cold start temperature [°C]
 i = considered component (HC, CO)
 $FzKonzept$ = vehicle concept (diesel, spark - ignition EURO3)
 t = time [s]

The work represents the cumulative sum of the power for overcoming the road resistances (P_{Road}), which are composed of the three components of rolling, air and acceleration resistance related to the nominal power (P_N).

$$Work = \int P_{rel} dt = \int \frac{P_{Road}}{P_N} dt = \int \frac{P_{Roll} + P_{Air} + P_{Accl}}{P_N} dt \quad (\text{Equation 1a})$$

In contrast to this, the Volkswagen approach (Nagel, 1999) assumes that the parameters which determine the size of the extra emissions can be described as a function of two temperatures. The engine-internal factors, such as increased friction and combustion losses as consequence of the cold engine are described as function of the cooling water temperature and the second factor, the degree of conversion of the catalytic converter is determined essentially by the temperature of the catalytic converter. This leads to the following approach for describing the emission behaviour during warm-up.

Volkswagen approach:

$$\dot{m}_{cold,i}(t) = WLF_i \cdot \dot{m}_{warm,i}(t) + WLZ_i \quad (\text{Equation 2})$$

with

WLF_i = warm - up factor $f(J_{H2O})$

WLZ_i = warm - up addition $f(J_{Cat}, \dot{m}_{fuel})$

J_{H2O} = cooling water temperature [°C]

J_{Cat} = catalytic converter temperature[°C]

Apart from cooling water and catalytic converter temperature, the fuel consumption or the CO₂ emissions are still used as input variables to be able to take account of the driving dynamics in the second term WLZ.

The emission time series, which were used for deriving the approach, are used with a precision of seconds in the evaluation. For deriving a functional relationship for describing the warm-up emissions it is necessary to suitably smooth the very unquiet emission curves. A frequently used smoothing operation is the so-called moving average. However, the disadvantage of the moving average is that this averaging possesses no parameters which can be changed for adapting to the cut-off frequency. By the use of the time-discrete Fourier transformation, the frequency components of the total emission measuring signal can be analyzed and made accessible to suitable filtration. To prevent a phase shift by the filter, a recursive filter is used. From the numerous classes of filters, which have been developed as standard methods for statistical analysis, the so-called Butterworth filter was used here. The Fourier analysis of the HC emission time series of numerous FTP-75 tests showed that the lower frequencies below 0.1 Hz dominate the emission curve. Therefore the cut-off frequency of 0.1 Hz was selected for the filter. Investigations with regard to the order of the filter resulted in that the 4th order filter represents a good compromise between computing effort and approximation to the original emission signal. Figure 5 shows the comparison between the filtered and unfiltered signal.

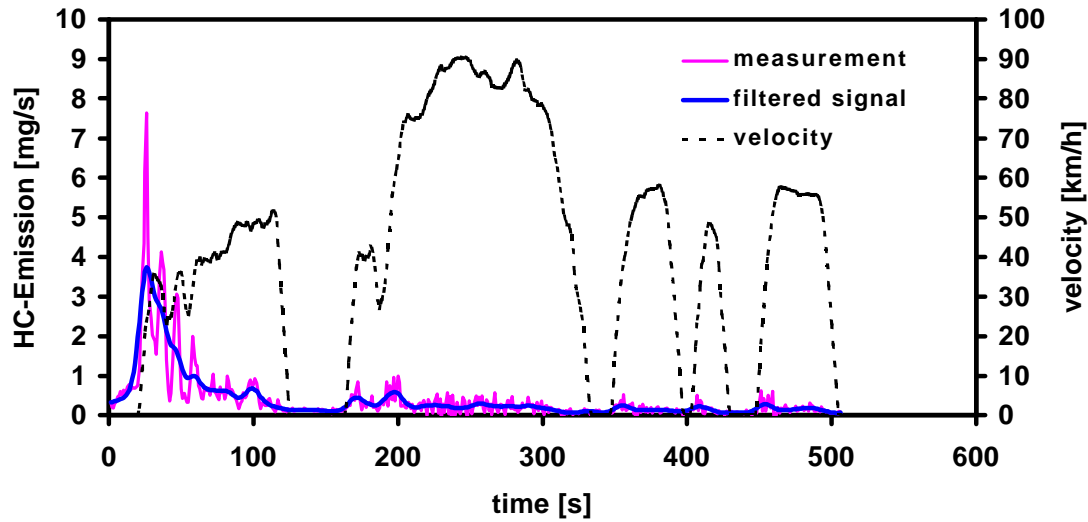


Figure 5: Comparison of HC measuring signal with filtered HC signal in the FTP-75

Messung = measurement, Geschwindigkeit = speed

The filtered information was used in (Equation 2). The following relationship for the two WLF and WLZ functions could be derived by regression analysis:

$$WLF_i = A + B \cdot J_{H_2O} \quad (\text{Equation 2a})$$

$$WLZ_i = C \cdot \exp(D \cdot J_{Cat}) \frac{\dot{m}_{fuel,cold}(t)}{\dot{m}_{fuel,idle}} \quad (\text{Equation 2b})$$

$\dot{m}_{fuel,cold}$ = fuel consumption of the cold engine [mg / s]

$\dot{m}_{fuel,idle}$ = fuel consumption of the idling engine [mg / s]

The derived functions represent a compromise between the number of necessary regression coefficients and the best possible adaptation of the function to the filtered measured values. If one compares the HC emissions calculated with the approaches of TÜV Rheinland and Volkswagen with the measured values in the FTP-75 cycle, then one receives the modal and cumulative HC emission curves shown in [Figure 6](#).

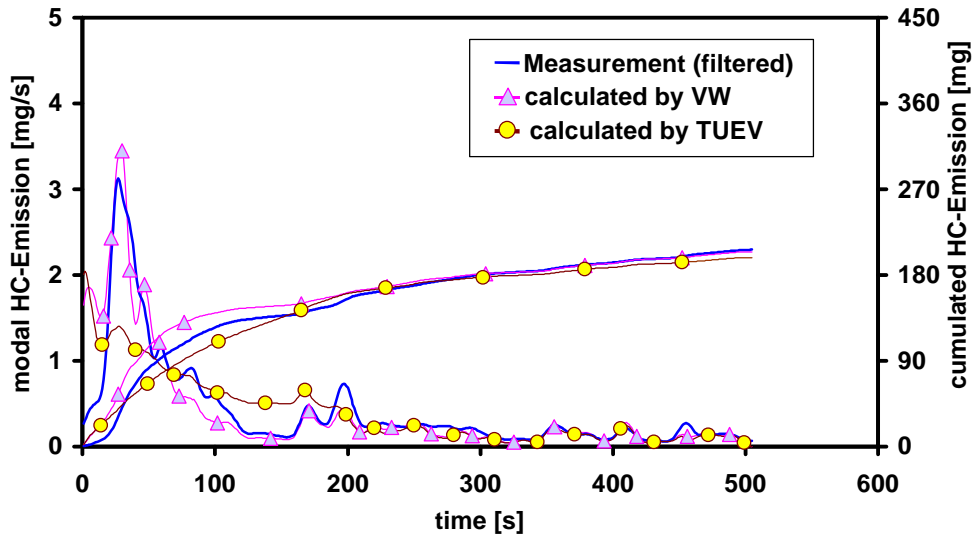


Figure 6: Comparison of the modal and cumulated HC emission measured values with the values calculated according to the approaches of the TÜV Rheinland and Volkswagen in the FTP-75 (Phase 1) (VW 1.9l TDI)

As expected, both approaches derived on the basis of this cycle reproduce very well the cumulated sum of the HC emissions at the end of the warm-up phase. The modal curve already illustrates the qualitative differences between the two approaches. Because of the strong smoothing (fixed mean values) and the 3rd order polynomial regression in the approach of the TÜV, the emission peaks directly after the start cannot be simulated.

The advantages of the approach of VW in comparison with the TÜV become clearer regarding the ability of both methods to be transferred to other driving cycles. For this purpose the urban part of the NEDC was simulated and the calculated modal and cumulated HC emission curves are compared with the measured values, see [Figure 7](#).

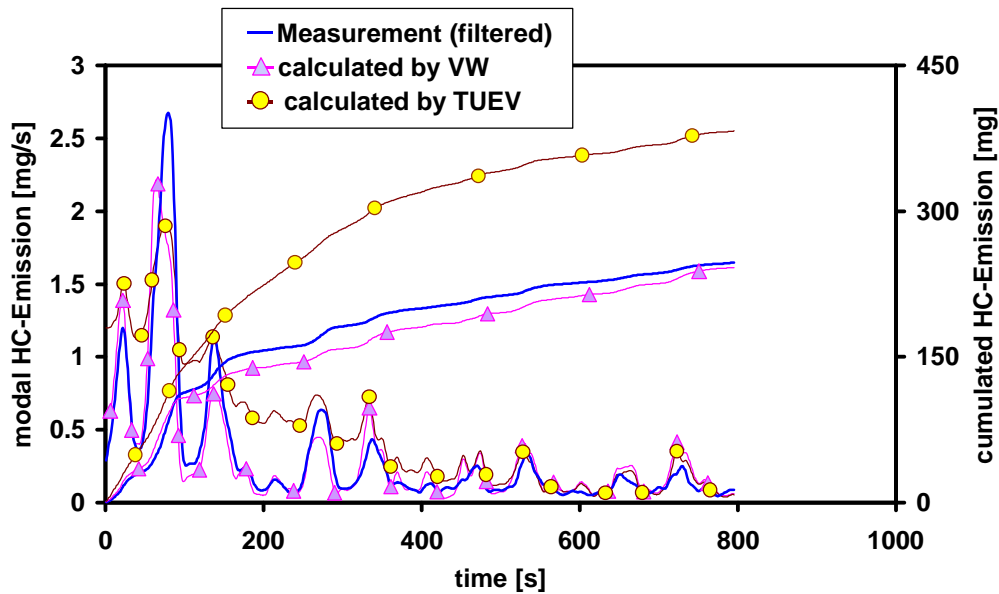


Figure 7: Comparison of the modal and cumulated HC emission measured values with the values calculated according to the approaches of the TÜV Rheinland and Volkswagen in the NEDC (urban part) (VW 1.9l TDI)

It is shown that the approach developed by Volkswagen also reproduces very well in the NEDC the sum of the uncombusted hydrocarbons at the end of the warm-up phase. The emission peaks occurring depending upon the engine load are also reproduced very well by this approach.

In comparison to this, the approach of the TÜV delivers HC emissions higher by 55% at the end of the warm-up phase. The modal curve shows an overestimate of the measured values especially in the range from 175 – 205s. In this delay and standstill phase, the integrand P_{rel} in equation 1a remains constant according to definition and thus also the calculated extra emissions.

The results for HC emissions shown in Fig. 6 and 7 are summarized in [Figure 8](#) and the CO, CO₂ and NO_x emissions, are shown as comparison of the computing results of both methods with the measured values in the FTP-75 and NEDC.

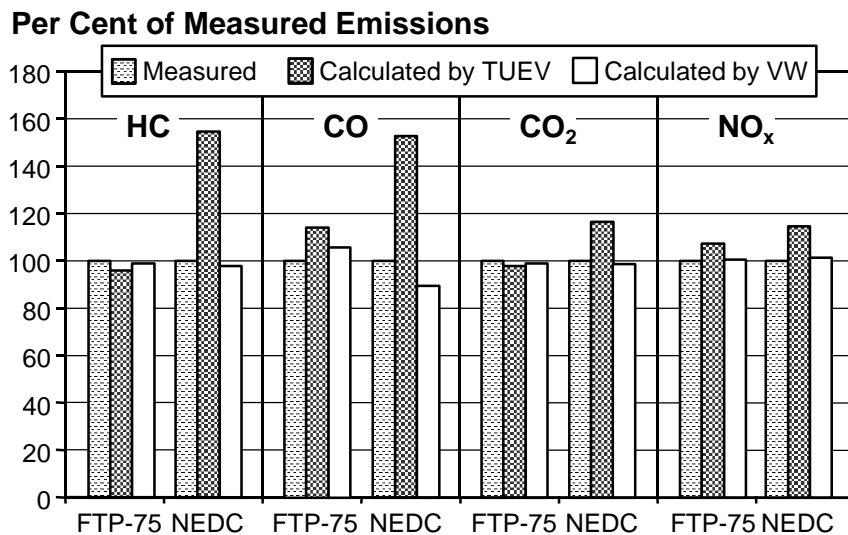


Figure 8: Measurement – calculation comparison for HC, CO, CO₂ and NO_x in different cycles

The approach of the TÜV Rheinland also indicates a clear overestimate of approx. 45% for the CO emissions at the end of the warm-up phase of the NEDC. The approach calculated by Volkswagen deviates in the NEDC from the total sum of the emissions at the end of the warm-up phase by around 10%, but still remains within the 95% confidence region stated in the figure. At the other components CO₂ and NO_x the overestimate is as expected lower, since these components are less influenced by cold starting.

Due to the good agreement of the calculation with the measurement both in the NEDC and in trips in real road traffic, it could be shown that the approach of VW derived from the investigations in the FTP-75 can be transferred to arbitrary driving behaviour.

The level of the cold start and warm-up induced extra emissions depends, apart from the driving behaviour, also upon the temperature of the engine at the start of the trip. Therefore the warming up and cooling down processes of the engine taking place during a day must be taken into account. To determine the temperature of the engine at the start of the trip, the standstill times and departure times known from the trip chains were transferred to the thermodynamic part model, which calculates the needed temperature of the cooling water and the catalysator. The parking areas provide in this case information about the location of each

vehicle during the standstill time. Due to this linking of traffic demand with emission model, both the extra emissions caused in the cold start and warm-up phase and the evaporation emissions occurring during cooling down can be calculated and assigned exactly in location and time. Furthermore the thermodynamic part model enables the cool start to be accurately modelled. The detailed description of the microscopic approach for calculating traffic emissions resolved in time and space taking special account of the warm-up behaviour can be found in Nagel (1999).

2.5 Microscopic flow and propagation model

To calculate the air quality, the commercially available, three-dimensional microscalar flow and propagation model MISKAM is used. This model also takes account of flowing around and flowing over of strongly broken down building configurations and thus is very well suited for forecasting wind distributions and air quality in streets and parts of cities.

To solve the three-dimensional movement equations in the model, the area under examination is subdivided into grid boxes. The calculated emissions must be divided over these grid boxes. When running through this grid box which is up to 20m in length, the exhaust gas emission quantities of all vehicles emitted in this section are acquired and accumulated for the period considered. These accumulated emissions are made available as input data to the propagation model. With addition of the background concentration, a distribution of the air quality for the area under examination can be produced.

3 CURRENT STATE OF DEVELOPMENT AND POTENTIAL

The state of development of the simulation software currently allows modelling of traffic situations restricted in location and time. In a sensitivity investigation, the control of the traffic lights for the traffic on a main traffic road was optimized as an example. Figure 9 shows the influence of changed traffic light controls on the emissions in the entire section.

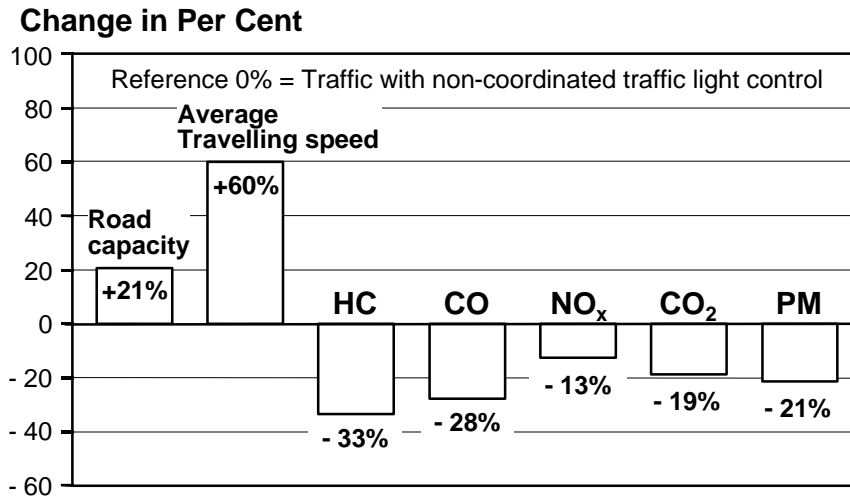


Figure 9: Sensitivity of changed traffic light controls on the emissions

Because of lower standing times in front of the traffic lights, the travelling speed and traffic intensity increases with simultaneous reduction of the emission level for all considered components.

However, after conclusion of the development work, the presented simulation system allows not only an inexpensive planning and quantification of the effectiveness of individual local measures but also measures throughout the network for improving the air quality. The integration of the individual models further allows optimization of the entire road traffic system from the origin of traffic up to air quality.

Due to linking the trip chain information with the thermodynamic part model and the new warm-up method, the traffic-induced emissions are accurately assigned in space and

time. With regard to the further calculation of the air quality in road canyons, the quality of the computing results is thus considerably improved.

The later area of application of the simulation software will be typically the simulation of large urban network sections. Joint use of the simulation software with the city of Braunschweig is planned.

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ACKNOWLEDGEMENTS

We thank all staff members of the Volkswagen Licensing Department in Wolfsburg, who have contributed under the management of Mr. J.-D. Baronick to the success of this work. Special gratitude is due to Mr. K. Kulpe for his excellent attendance to the mobile exhaust gas measuring system.

Furthermore we thank all staff members of the traffic planning, construction and surveying departments of the city of Braunschweig, especially Mr. Pottgießer (traffic planning office), for making available the input data, their technical support and the good cooperation.