AN INSTANTANEOUS EMISSION MODEL FOR THE PASSENGER CAR FLEET

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ABSTRACT

At the Transport and Air Pollution Conference 2005 the improvement and application of the PHEM instantaneous emission model for passenger cars and light duty vehicles was presented. Instantaneous emission measurements from chassis dynamometers were used to create engine maps for the passenger car fleet, including gasoline and diesel vehicles EURO 0 to EURO 4.

Measurements were collected from the TUG chassis dynamometer with the evaluation of the tests conducted automatically. Engine emission maps could not be created for particulate mass, as only three values were available for each CADC (Common Artemis Driving Cycle) test that populate the model. Particulate mass was originally linked to HC-emissions. This method has been improved, with instantaneous particulate matter emissions linked to a transient particle number signal that has been recorded for every test. A comparison of simulation results and measurements is provided for EURO 3 and EURO 4 vehicles.

It is possible to link PHEM with traffic microsimulation tools, such as AIMSUN or VISSIM, and subsequently dispersion models (e.g. GRAL and MISKAM). One application of PHEM linked with the traffic microsimulation AIMSUN is also presented in this paper. The combined traffic and emission modelling framework was used to predict the influence of a "Low Emission Zone", which excludes EURO 0 to EURO 2 diesel passenger cars from entering a controlled area. The traffic flow profiles were simulated by AIMSUN and then the emissions calculated by PHEM.

Keywords: *Instantaneous emission model, traffic simulation, particulate mass, particle number emission.*

1. INTRODUCTION

The model PHEM was initially developed for heavy duty vehicles, using measured emission maps available from an engine test bed. PHEM calculates the necessary engine power to overcome the driving resistances and the losses in the transmission line for the vehicles. The actual engine speed is simulated by a drivers gear shift model and the actual transmission ratios. The simulation of engine power demand and engine rotational speed is completed at a 1 Hz resolution over the driving cycle. The emissions are then interpolated from the engine map for each second. The results are corrected according to the actual dynamics of the cycle (e.g. deviation of engine power and speed). This transient correction tool improves the accuracy especially for HC, CO and PM. Integrating the instantaneous emissions over the cycle provides a straight-forward total emission measure.

A method was presented at the Transport and Air Pollution Conference 2005 to generate emission maps from instantaneous chassis dynamometer emission measurements. For this task the emissions in each second of the cycle are allocated into the engine map according to the actual engine power and the engine speed of this second. To achieve accurate alignments between emissions and engine load, the instantaneous measured emissions are corrected as to the time delay of the analyzer and the variable transport time in the measurement system. This method is applicable for gaseous emissions (CO_2, CO, HC, and NO_x), but not for particulate mass as no transient measurements are available. For the particulate mass simulation an adapted HC emission map was used, but the model performance was insufficient. Due to the significant increase in the proportion of diesel vehicles and environmental implications, it is important that the particulate mass simulation is improved.

Ivanisin (2004) demonstrated that the emission map for particle number corresponds well with that for particulate mass, for both passenger cars and heavy duty vehicles. The measurement of particle number requires the nucleation of condensation particles to be suppressed; otherwise the correspondence with the particulate mass is poor. Therefore it was investigated using four diesel passenger cars if an improvement in the accuracy of PM modelling can be achieved by deriving instantaneous particle mass emission values from the instantaneous particle number data. Since the particulate number signal is recorded at every driving cycle on our chassis dynamometer, the method described would allow to set up PM emission maps quite cheap and would also provide particle number emission maps, which may be needed in future air quality modeling tasks.

An emission model of the passenger car fleet based on engine maps, requires a representation of the average vehicle for each EURO-category and fuel type. The share of each group on the total mileage driven can be given as model input. PHEM is able to accept inputs from traffic microsimulation models, and provide outputs to dispersion such as MISKAM or GRAL.

2. TEST PROGRAM

Although it is known, that the general correlation between particle mass and particle number emissions is rather poor, the correlation may be sufficient for single vehicles in single driving cycles to gain information on the instantaneous course of the PM emissions over the cycle.

In the test program the particulate mass and the particulate number emissions were measured simultaneous on the chassis dynamometer in various transient cycles (NEDC, CADC and the HBEFA cycles). The tests for two of the cars included 13 constant engine operation points which covered the whole CADC operating range.

2.1. Test vehicles

The four vehicles used for the evaluation tests are documented in Table 1. The vehicles are from different manufacturers. None of the vehicles have a DPF.

Table 1: Measured passenger cars

make	model	displacement [ccm]	power [kW]	injection system	EURO-category
Peugeot	307 HDI	1997	66	Common-Rail	EURO 3
Mazda	3	1560	80	Common-Rail	EURO 3
Opel	Astra H	1686	59	Common-Rail	EURO 4
Volkswagen	Golf V	1896	77	Pumpe Düse	EURO 4

2.2. Measurement equipment

The particle measurements on the chassis dynamometer employed a dilution system, which was developed at the FVT, e.g. Winkler (2008). The dilution system was used in combination with a condensation particle counter (CPC), see Figure 1.

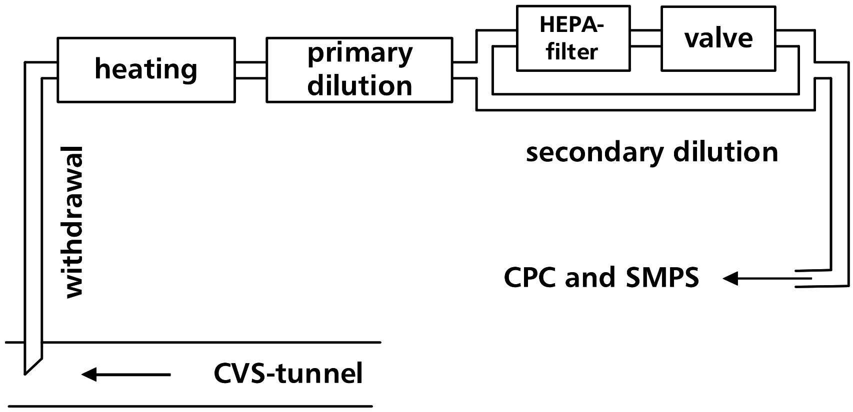

Figure 1: Configuration of the dilution system for particulate number measurement

A partial flow is taken from the CVS-tunnel. In the heating line the exhaust gas is heated up to 280°C which leads to the evaporation of liquid parts of the exhaust gas. In the primary dilution the exhaust gas is diluted with conditioned and filtered air. With that dilution a re-condensation of the volatiles in the exhaust gas after the dilution system should be inhibited. The exhaust gas is then split into two parts, one part is filtered with a HEPA-filter (High Efficiency-Particulate Airfilter) and the flow through this section is adjusted by a valve, which controlles the secondary dilution ratio. At the moment the system has been slightly re-designed to filfill all demands within the PMP-group proposal (mainly to heat the sample after the first dilution step, instead of in advance).

2.3. Measurement results

Figure 2 presents the particulate mass and particle number engine maps of for the EURO 4 VW Golf. The original particulate mass emission map has an extremely high value for only one full load point, making comparisons difficult. This particulate mass peak occurred when the engine overheated during testing on the chassis dynamometer. When excluded, there is an improved correspondence between the particulate mass and particle number (PN) maps.

With the link between particulate mass and particle number emission maps demonstrated, a simulated particulate matter signal can be generated based on the particle number emission map. To convert the particle number signal into a particle mass signal a specific mass [g/counted particle] is calculated for each of the three CADC parts (urban, rural and motorway). These values are then multiplied with the particulate number signal for the entire CADC sub-cycles. This signal for particulate mass is processed in PHEM as for gaseous emission species and rasterised in an engine map format.

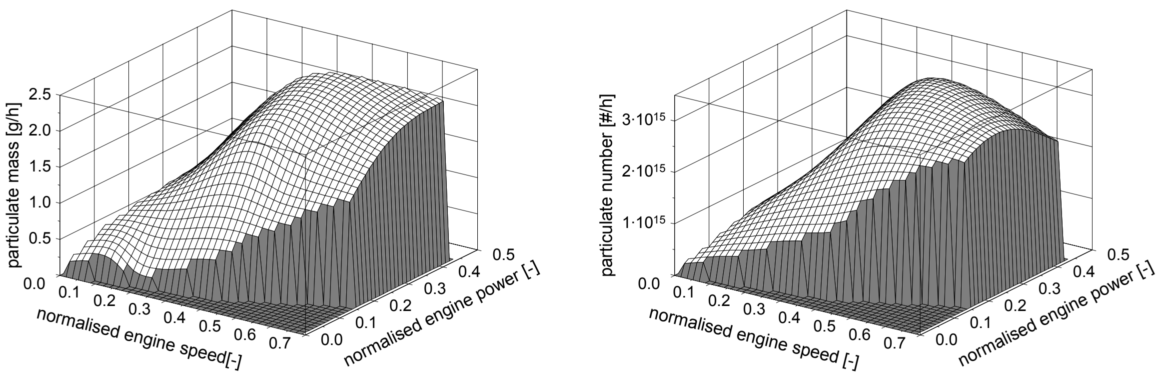

Figure 2: Particulate mass and number engine map of the EURO 4 VW Golf without the full load point

Figure 3 shows a comparison of the stationary measured particulate mass map with the particulate mass emission map gained with the method described from the tests in the three CADC parts. The correspondence of the two particulate mass maps is satisfactory, but at low engine load and engine speed an over-estimation is visible. This could be explained by transient effects, such as the turbo lag during accelerations from idling which leads to a lower air to fuel ratio and thus potentially higher PM emissions compared to steady state conditions. However, also artefacts in the PN measurements influence the maps, as discussed below.

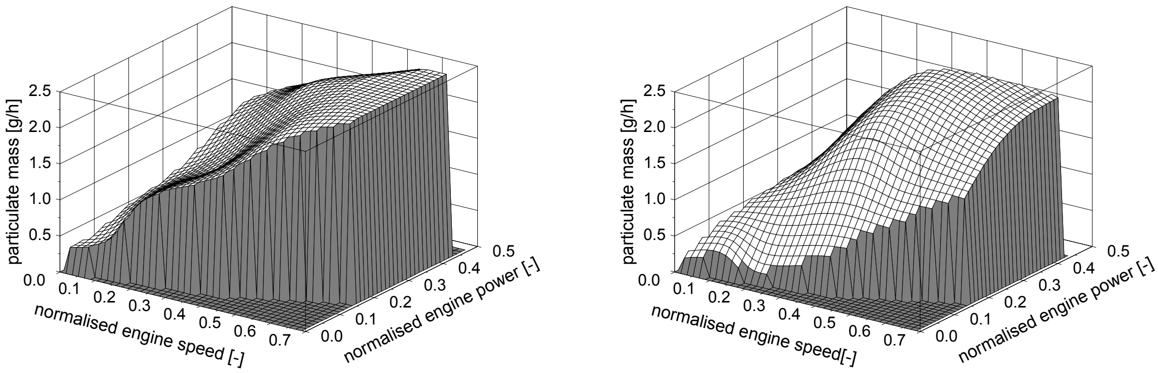

Figure 3: Comparison of the dynamic particulate mass map (left) with the stationary particulate mass map (right)

To gain accurate engine emission maps from transient test cycles a sufficient time allocation of emission signal, engine power and engine speed is crucial. Slow signals from the emission measurement system lead to inaccurate alignments in the engine map since the signals for engine speed and engine power are very fast. While these effects have been studied for gaseous exhaust gas components already, quite detailed and methods have been established to correct the analysers signal for mixing effects and variable transport times of the exhaust gas, e.g. Le Anh (2005), Ajtay (2005) the time resolution of the PN signal was as yet unknown.

The dilution system used at the TU-Graz was improved during 2007/ 2008 with the delay time now reduced to a low level. Figure 4 shows the measured particulate number emissions in the CADC urban. On the left side the results of our actual dilution system are shown while on the right side one test at the beginning of the development of the dilution system is given. The comparison shows quite clearly, that the former dilution system leads to a quite bad time resolution. The new system behaves much better but further significant improvements can be expected. Unfortunately the dilution system used for all testing does not use the 'new' dilution system. Thus the quality of the transient particle maps is influenced to a large extent by the slow and smoothed PN signal.

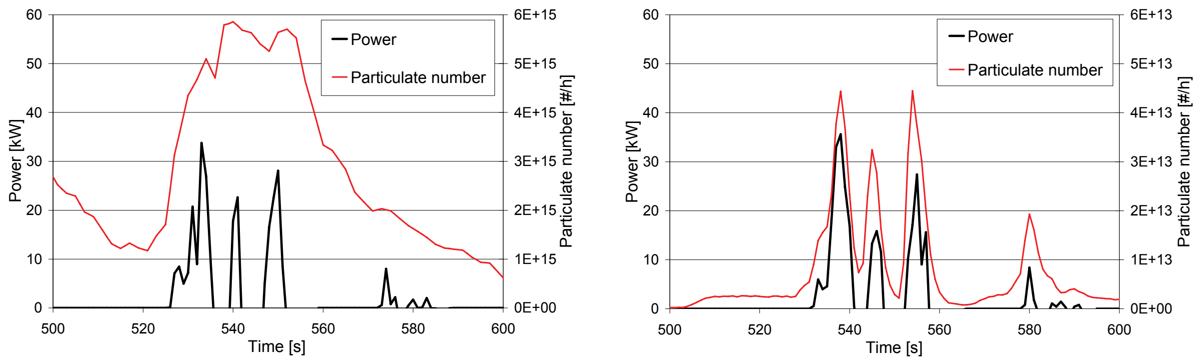

Figure 4: Improvements in the particle number emission measurement dilution **s**ystem: **a/** Early prototype **b/** New system

3. SIMULATION RESULTS

Figure 5 shows the simulation results for the two EURO 4 vehicles for different driving cycles. The engine maps were set up from the CADC cycle only. The simulation predictions are quite good results for both vehicles in most driving cycles, except the NEDC and the HBEFA cycle R4 for the VW Golf (Fig 5a). The deviation between measured and simulated results for the Opel (Fig 5b) is higher for the NEDC cold start test, but better for the CADC urban with a cold start prediction.

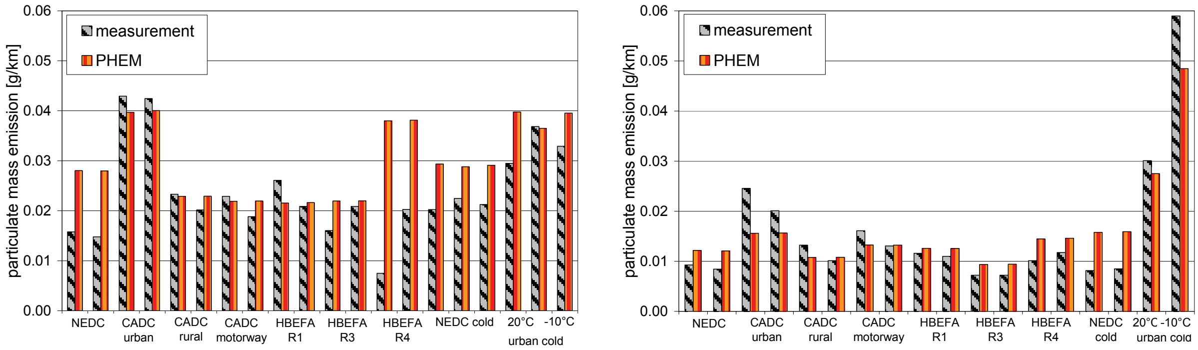

Figure 5: Comparison of the measured and simulated PM-emissions for different cycles for the two EURO 4 diesel vehicles tested a/ Golf b/ Opel

For EURO 3 the same trends as for EURO 4 diesel vehicle were found.

Figure 6 shows a comparison of the predicted particulate mass emissions for the handbook cycles (R1 – R4) of the average EURO 3 and EURO 4 diesel vehicle with the values for that vehicle category in the handbook, Keller (2004). Certainly the vehicle fleet in the handbook is different to the vehicles tested in this paper, thus the comparison can only be used to understand the general range of PM emissions. The handbook emission factors for diesel EURO 3 as well as for EURO 4 are calculated with reduction factors from the EURO 2 emission factor, thus the (limited) number of cars in PHEM should be closer to the reality. In the current version of PHEM, already tests on 8 EURO 3 and 5 EURO 4 cars are implemented, with the EURO 4 fleet consisting of 12 tested vehicles. The handbook however is planned to be updated with actual test results at the end of 2008.

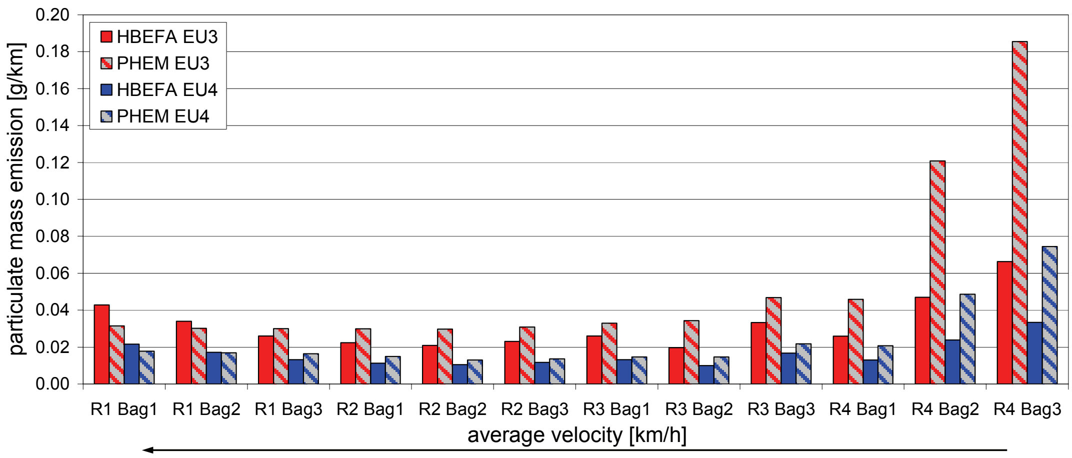

Figure 6: Comparison of the measured Particulate Mass emissions with the values of the HBEFA handbook of emission factors for diesel EURO 3 and EURO 4 passenger cars

For both, EURO 3 and EURO 4 the correspondence of the simulation with the handbook values is in all sub-cycles good excepted for the Stop&Go cycles (R4 Bag2 and R4 Bag3). A reasonable part of the high PM emissions predicted by PHEM for these low load cycles may be due to the described shortcomings of the PN measurement system. The slow PN signal leads to a systematic overestimation of points at the lower load range of the map. Typically these points are reached transiently from higher load points and the smoothed PN signal mixes higher emission levels from the load points driven before into the signal for the low load point. For high loads the effect is vice versa.

4. PASSENGER CAR DATABASE

Until now the PHEM passenger car database is filled with 61 passenger cars with different EURO categories, see Table 2.

Table 2: Passenger car Database of PHEM of the different EURO categories

	Gasoline	Diesel
Pre-Euro 1	3	Depicted with EURO 2
EURO 1	Depicted with Pre-EURO 1	Depicted with EURO 2
EURO 2	Depicted with EURO 3	5
EURO 3	8	10
EURO 4	23	12

34 gasoline vehicles are included in the PHEM database, whereas the EURO 1 emission map was generated with the PRE-EURO 1 emission map by lowering the emission level to the EURO 1 range. The EURO 2 emission map was generated with the EURO 3 emission map by increasing the emission level. For the diesel passenger cars 27 measured vehicles are in the PHEM database, whereas the PRE-EURO 1 and the EURO 1 were generated with correction factors from the EURO 2 emission map.

5. APPLICATION OF A TRAFFIC MICROSIMULATION MODEL LINKED WITH PHEM

5.1. Traffic microsimulation modelling

Microscopic traffic simulation models are becoming increasingly popular tools to analyse traffic operations and evaluate management strategies on both inter-urban and urban road networks. Traffic microsimulation models simulate (stochastically) vehicle movements and interactions through a well-defined road network. The simulation is updated at a fixed time increment (e.g. 1 or 2 Hz) according to vehicle operating characteristics (performance and desired link speed) and rules that govern car-following, lane-changing, gap acceptance and driver behaviour at intersections (Liu et al, 1995).

As traffic microsimulation models simulate the space-time trajectories of all vehicles through a network, this disaggregate information can be collected and supplied to instantaneous emission models such as PHEM. Although many studies have successfully linked traffic microsimulation and instantaneous emissions models, in the majority of cases the characterisation of the vehicle fleet has been limited. In this study the ‘AIMSUN NG’ traffic microsimulation software (TSS, 2005) was used to model a congested urban road network. The microsimulation model was systematically calibrated and validated. All modelled vehicle trajectories were extracted and supplied to PHEM.

5.2. Case Study: Evaluation of a theoretical Low Emission Zone policy

The linked AIMSUN NG and PHEM modelling framework was applied to a congested urban road network in the City of York (UK). The model was developed in a previous study (Tate et al, 2006) and had importantly been rigorously calibrated and validated. To demonstrate the capability of the modelling framework, two 'theoretical' management policies/ scenarios were contrived and implemented. The policies devised were Low Emission Zones (LEZ) for diesel passenger cars. LEZs aim to improve air quality by restricting the most polluting vehicles from being driven in sensitive areas. Restrictions are typically applied according to vehicle type and emission category. In this desktop study, all Euro 2 and older diesel passenger cars were excluded from the network. As an up-to-date, detailed distribution of the City of York vehicle fleet (e.g. Euro 1 - 5, fuel and vehicle type) was not available, the fleet distribution for an Austrian urban street in 2008 was adopted. The Euro 2 and older diesel passenger cars represent 10.7% of the light-duty vehicle mileage. Three scenarios were modelled:

- BASE situation (2006 traffic demand levels and 2008 Austrian fleet distribution);
- Scenario 'A' (LEZa): Cleaner light-duty vehicle fleet (Euro 2 and older diesel replaced by newer cars according to the average mileage distribution of the SI-cars and the EURO 3 and EURO 4 diesel-cars), traffic demand assumed un-changed (BASE situation);
- Scenario 'B' (LEZb): Euro 2 and older light-duty diesel vehicles excluded from both the network and fleet distribution (resulting also in -10.7% vehicle mileage on the network).

In reality the reduction in vehicle trips would be lower than for 'Scenario B', due to: suppressed demand effects, and the local vehicle fleet distribution would in all likelihood change in light of the management policy. These effects were not accounted for in this 'theoretical' scenario, thus the Scenario 'B' shows the upper bounds of the potential policy impact. On the other hand Scenario 'A' may show the lower bounds since it assumes a complete substitution of all banned vehicles..

5.2.1. Test Network

The historic buildings in the city of York have constrained the expansion of the road network, which regularly becomes congested during and outside peak periods. The small test network comprises 6 signalised intersections and represents an average evening peak hour (17 to 1800hrs). The analysis focussed on one over-capacity approach (Bootham Road) to a signalised intersection (Bootham/ Gillygate), as illustrated in Figure 7. The 'base' network conditions were well-specified using digital overlay mapping, the physical characteristics of the road network, and the data relating to traffic demand. The characteristics of the network (including public transport services) were either supplied by City of York Council 'Transport Network Manager', or collected during a field survey. Data made available from four automatic count sites operational in the study area were analysed to determine average link flows. A 'priori' OD matrix was up-dated with the observed link flows. Journey time surveys (number plate matching method) were conducted along the Bootham Road approach. Local driver behaviour was also studied using two Instrumented Vehicles equipped with a high frequency GPS and CAN bus link (Tate, 2005).

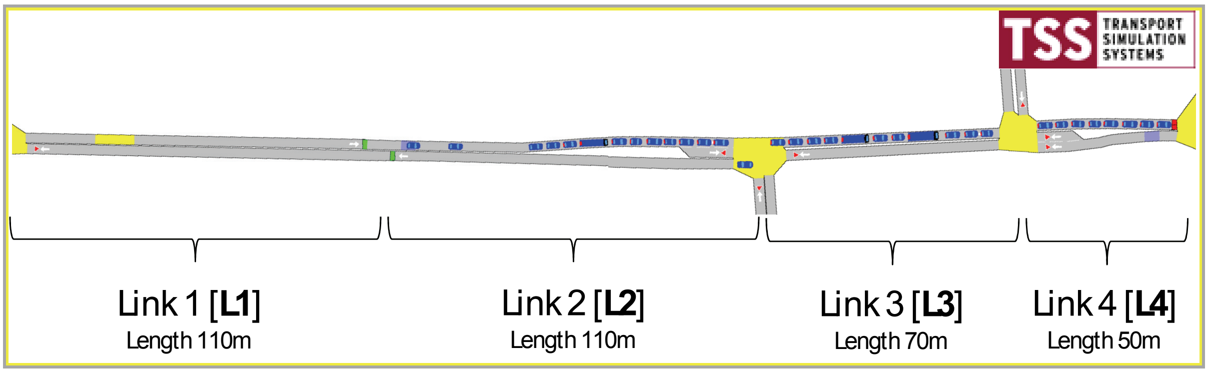

Figure 7: Focussed Network Schematic of Key Links (AIMSUN NG 2D Output)

The network calibration procedure adopted was based on the guidelines proposed by Dowling et al (2004). Reviewing the input data and the 2D simulation animation allowed errors generated during setup/ network coding to be identified and corrected. The impact of changing selected calibration parameters within acceptable boundaries was also tested, namely: the simulation step (0.25, 0.5, 0.75 and 1.0 secs), arrival pattern distributions, links' maximum speed, and particularly relevant to this emission study the vehicle maximum acceleration rates. The calibration 'measures of performance' adopted, were:

- Capacity – observed/ modelled detector flows; and
- System – observed/ modelled journey times).

The model calibration criteria target values selected were: link flows within 85% in all cases, and journey times varying within 15% in 85% of cases. The number of replications for each experiment was chosen to be 10, in-line with other studies (Liu et al, 1995). The majority of 'global' simulation parameters were set to default values. However, previous Instrumented Vehicle measurements in the study area (Tate et al, 2006) suggested that for the narrow, congested York street environment, lower average 'desired' link speeds and vehicle performance parameters should be adopted. The calibration procedure identified the: Simulation step as 0.5secs (2Hz), Arrival pattern - 'Constant', vehicle acceleration as observed - 1.85ms^{-2} (Stdev 0.43) and Link speed limits of 40 kmh^{-1}. Model validation was carried out using dis-aggregate data from the Instrumented Vehicles. The maximum acceleration rate, defined as the initial acceleration following a stand-still, was calculated from both the observed and modelled trajectory datasets. This acceleration rate was calculated by differentiating vehicle speed at a frequency of 2Hz, then applying a four point moving average. The mean observed value was 1.31ms^{-2} (±0.46), whereas the comparable modelled value was 1.33ms^{-2} (±0.37). As these values are statistically similar, the model is considered to be calibrated satisfactorily for the 'maximum acceleration' parameter. Figure 8 illustrates the distribution of vehicle speeds/ acceleration for the key road links/ sections (L1 to 4).

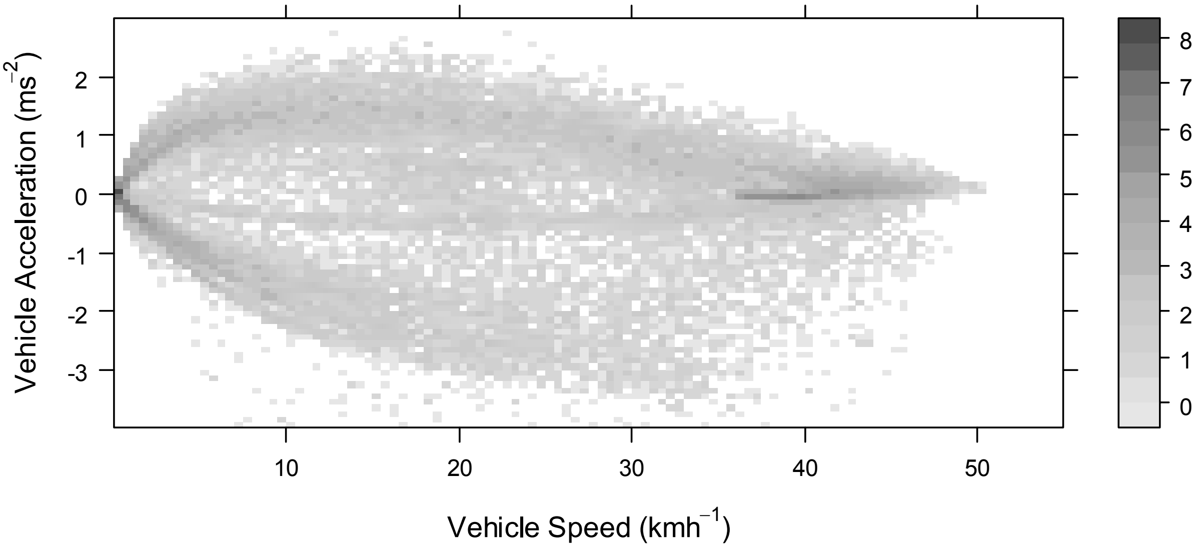

Figure 8: Simulated vehicle speed/ acceleration frequency distribution (log-scale)

5.2.2. Results

The simulated trajectories of all vehicles, classified by vehicle type for each of the 3 scenarios (with 10 replications) were recorded and supplied to PHEM. Comparisons of the average link speed and total fuel consumption/ PM and NO_X emissions for the 'BASE', 'LEZa' and 'LEZb' scenarios by road link are presented in Figure 9. Note the variation between simulation replications is presented. A weighted mean summary is also presented in Table 3.

The 'BASE' network is severely congested, with a queue propagating over 250m back from the signalised intersection stop-line. The mean section speed of Link 1 ('L1') is therefore low. The variation between replications is also significant (~25kmh^{-1}). Traffic is also consistently queuing on 'L2 -4', indicated by the low (<7kmh^{-1}) average speed. With the reduced demand in the 'LEZb' scenario, the queue of traffic does not propagate back to 'L1', indicated by the higher section speed. In this scenario vehicles travel along 'L1' at an approximately constant speed (cruising mode). 'L2' intermittently contains queuing traffic in the 'LEZb' scenario as the variation in average section speeds is significant. Closer to the intersection stop-line, with queues developing and dissipating with each cycle of the traffic signals, average link speeds are low for all scenarios. The changes to fuel consumption and emissions (NO_X, PM) are consistent with our understanding that these are elevated in stop-start driving conditions due to periods of idling and transient, higher power operation. Fuel consumption and emission benefits of the 'LEZb' scenario are therefore greatest on the links furthest from the intersection. Adjacent to the intersection ('L4') the emission benefits are in-line with the reduced demand and cleaner vehicle fleet. It is interesting to note that although newer vehicles are 'cleaner' in terms of local air quality, their fuel consumption and CO_2 emissions tend to be higher with the burden of lower NOx emission limits and increasing vehicle weight.

The modelling demonstrates that by simply enforcing an accelerated fleet modernisation, with no change to flow and congestion levels, a modest reduction in NO_X (7.8%) and PM (11.7%) emissions is predicted. If traffic demand is also reduced by ~10%, congestion problems can be largely relieved, resulting in more efficient, reliable and less environmentally damaging traffic networks. In this 'theoretical' scenario NO_X emissions are forecast to decrease by 45% and PM 50%.

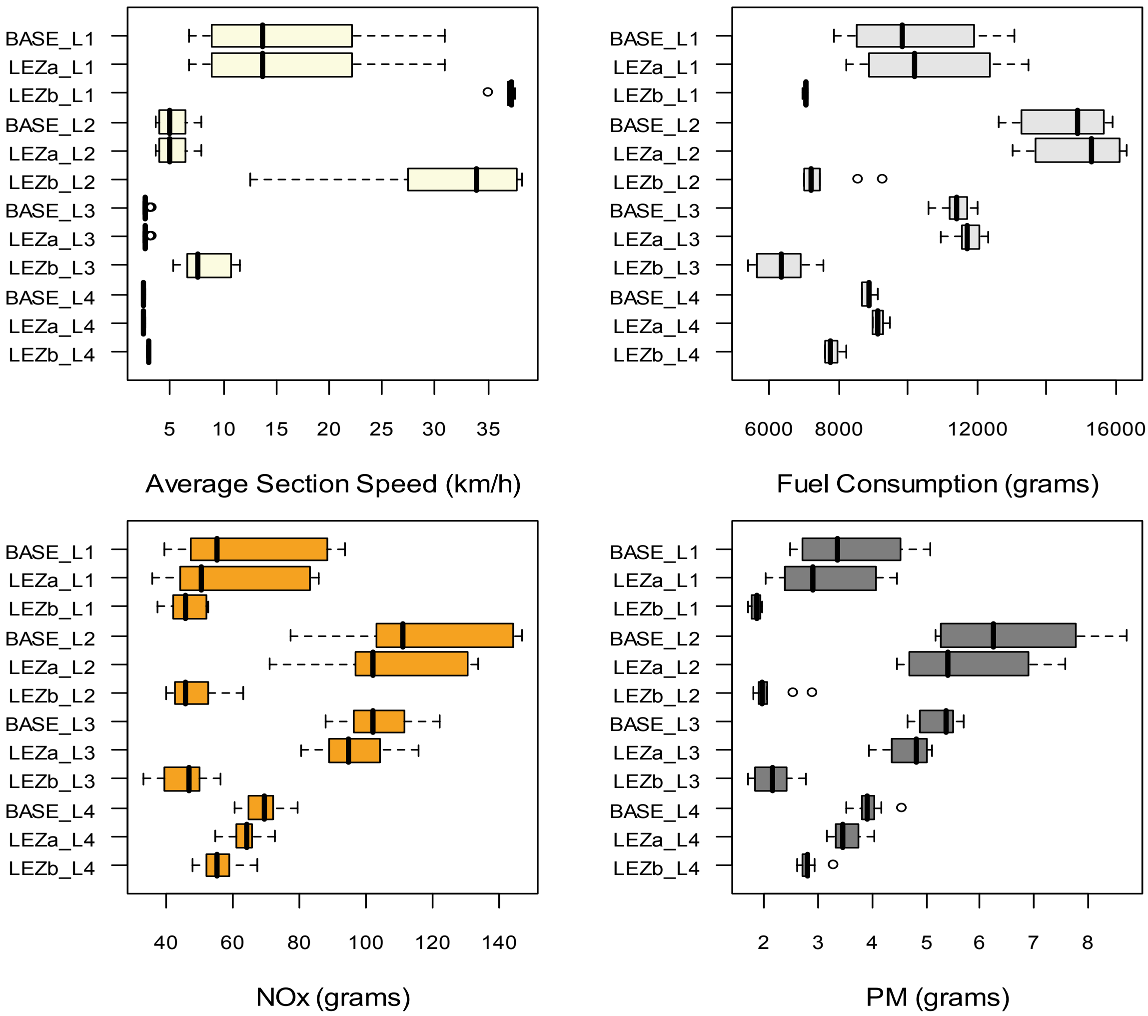

Figure 9: Evaluation of the impact LEZ impact
(Notation: BASE_L1=Base scenario Link 1, 'LEZa'=Cleaner fleet, 'LEZa'=Cleaner fleet and reduced demand)

Table 3: Weighted average results summary

Scenario	Speed (kmh-1)	Fuel Cons. (kg)	NO_X (g)	PM (g)
BASE	4.68	11.92	96.9	5.32
LEZa	4.68	12.38	89.3	4.70
LEZb	11.82	7.39	52.2	2.47

6. SUMMARY

With the increasing importance of PM emissions in air quality tasks, it is important a method is devised to adequately treat this exhaust gas component, at a sufficient accuracy to keep the instantaneous emission modelling approach attractive. Instantaneous models advantages include the modest demands on the number of tests they demand from roller test beds, and the potential to calculate new sets of emission factors for any new data on the driving behaviour.

In the future the particle number emissions (PN) are likely to become an important exhaust gas component and many test beds already apply particle number emission measurements in standard programs. Thus it was obvious to attempt to link the particle mass emissions to the instantaneous particle number data. Since the correlation of particle number and particle mass is known to be poor at an aggregate level, it was necessary to test if the correlation was sufficient for individual test runs, which are used to populate the engine emission maps from transient test cycles. Four diesel passenger cars were used for this task. Detailed measurements of particle mass and particle emissions in transient and steady state load conditions were performed. While the correlation between mass and number emissions in steady state tests was sufficient, the measurement set up for particle number measurements in transient test cycles was found to need improvements in terms of transport time in the dilution system and a reduction of the resulting 'smoothing' effects of the PN signal. As the time allocation of the actual engine load and the PN emission level is inaccurate, this leads to model discrepancies, such as overestimations of PN emissions at low loads. The results achieved so far have however allowed the creation of engine emission maps not only for gaseous emissions but also for particle mass and particle number emissions from one standard test. The current version of the dilution system already has a significantly improved time response and further improvements are likely.

Data available from 61 passenger cars were added until now to the PHEM model database. As a result PHEM is now able to simulate average fleet emissions for both, passenger cars and heavy duty vehicles on an instantaneous basis.

PHEM has been linked with microscopic traffic models, and the outputs have been supplied to air quality models. The PHEM user is able to define the proportion of the total vehicle mileage for each EURO classification, fuel type and vehicle category. PHEM then selects for each vehicle in the network a corresponding class for the simulations.

A linked traffic microsimulation (AIMSUN) and PHEM modelling framework was applied to a congested City of York network, to investigate the effects of a Low Emission Zone (LEZ). The contrived LEZ Policy excluded Euro 2 and older light-duty vehicles from entering the controlled area. To assess potential effects, two scenarios were devised. In the first, the older diesel cars were assumed to be substituted by newer vehicles, so the demand and flow levels from the base situation were maintained. The proportion of diesel EURO 0 to EURO 2 was set zero. This is assumed to represent the lower bound of the potential of this measure. The second scenario assumes all of the vehicle trips performed with the Euro 2 and older diesel cars are removed from the network. This results in 10.7% less light-duty vehicle mileage across the network and certainly gives the upper range of the effects on emissions.

The modelling results indicated that an accelerated light-duty fleet modernisation, with no change to flow and congestion levels, would only achieve modest reductions in NO_X (7.8%) and PM (11.7%) emissions. If traffic demand was also reduced, by approximately 10%, the congestion on the network would be largely eliminated. With polluting stop-start driving and periods of idling dramatically reduced, the predicted emission reductions were 45% for NO_X and 50% PM. Fuel consumption (and therefore CO_2 emissions) across the network was predicted to decrease by 38%. These significant benefits are encouraging evidence for transport policy makers and planners, aiming to develop management strategies to reduce the environmental impact of road traffic.

7. ACKNOWLEDGEMENTS

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