Refined vehicle and driving-behaviour dependencies in the VERSIT+ emission model

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Abstract
The demand for local and time-dependent emission predictions, in combination with new time-dependent modal-mass and mobile PEMS measurements induced major changes in the VERSIT+ emission model of TNO. The current version is the third, after the second major revision and has two major differences with the previous approach. First, an individual analysis is added of each of the more than 3200 vehicles in the measurement programme, to separate properly the vehicle dependence from the driving-behaviour dependence. The other development is a closer linkage to instantaneous emissions depending on velocity and acceleration. This enables the use of both modal mass measurement data and the older bag data in the same model. Due to the improvements, the VERSIT+ is now tuned toward the future. The model enables the consistent calculation of road traffic emissions for a wide range of different real world conditions. Accurate emission factors for national emission inventories can be calculated, but also the effect on the local emissions due to traffic measures can be evaluated.

Keys-words*: emission model, in-use compliance, road traffic emissions, emission factors, driving behaviour.*

1 - INTRODUCTION

Road traffic emission models serve a variety of purposes. They may be used in for instance emission inventory studies, to determine the total, annual and national emissions of all vehicles, and relate these numbers to the average emission of a fleet-average vehicle in a generic category, like a passenger car or a heavy-duty truck. Another purpose is to test the compliance with emission regulations. Beyond this compliance lies a further goal to make the regulations fitting for the problems they are meant to solve.

A completely different purpose of emission models is to assist the development of new technology, by precise knowledge of the circumstances of the vehicle and the engine at which the unwanted emissions may occur. These emission models are meant to supply a direct, experimental link between vehicle operation and emissions.

Another direct link has received much attention over the last five years. This is the direct link between emissions and local air quality. In many urban areas where the air pollution exceeds the limit, there is a substantial traffic-related contribution. Therefore, the wish to monitor and to take effective measures has grown. The emission models are one part of the missing link between road traffic and the deterioration of air quality. The other part is the dispersion model; how the exhaust gases spread in the air.

The VERSIT+ emission model has been the Dutch road traffic emission model for many years for mainly the first goals: the average emissions in a variety of circumstances, for present and future fleet decomposition. The effects of planned government policies lead to changes in fleet composition, fleet usage and age, with corresponding effect in the gross emissions.

These emission factors form part of the basis of the environment reports submitted by the local governments. A simple dispersion model links the daily traffic intensities with air-quality, which is for instance done in the Dutch CAR model. The results produced by these models, are largely based on averages and there produce as many questions as answers if used to estimate the effect of traffic related measures. Many variations in the traffic situations, local road planning, or fleet composition will not be visible in these results.

A new version of the VERSIT+ emission model is developed, partly as an improvement of the present version, and partly to be able to accommodate the questions concerning local effects of traffic management and fleet rejuvenation. This development is explained in this paper.

2 – EMISSION MODELS

Recently, a number of reviews were produced which compare the well-known emission models in the world. VERSIT+ plays a special role, since it is closely related to the Dutch in-use compliance program. Furthermore, due the complexity and sensitivity of handling this data-set and the large amount of driving cycles used for testing, the model is not easily transferable.

VERSIT+ is a statistical emission model able to calculate real-world HC, CO, NO_x, NO_2, PM_{10} and CO_2 emissions of road vehicles. It is best seen as an analysis tool of a large set of emission measurements of the Dutch fleet, mainly performed in the in-use compliance programme. Over 20.000 measurements with warm and cold engines on over 3.200 different vehicles have been performed in a period over twenty years. The vehicles were randomly selected from the commonly sold models and were requested from their owners, to participate in the testing program. The average maintenance state of the vehicles should therefore correspond to the Dutch situation. Furthermore, new technology has always been included in the VERSIT+ model to be able to estimate their effects of their mass introduction.

The emission results themselves are already representative of the Dutch situation, since besides type-approval tests like the NEDC and the FTP, in most cases real world driving cycles, like the CADC, OSCAR en Dutch F&E cycles, are used to characterize the driving behaviour for which the emissions are determined. Every vehicle is tested typically on five different tests, but some on many more, as in the cases of durability testing.

To develop an emission model for a given driving behaviour and vehicle type from the large set of vehicles, driving cycles and emission measurements a detailed statistical analysis is required. Two main ingredients are the distinction of relevant vehicle categories, with similar emission characteristics, and the characterization of driving behaviour in relevant parameters on which the emission actually depend.

The vehicle categories are generally straightforwardly based on fuel, emission standard, injection technology, after-treatment technology, and transmission. The disadvantage of making such a detailed distinction is insufficient data in some of the categories, while on the other hand automatic transmission and older injection technology will strongly affect certain emissions, of these cars.

The characterization of driving behaviour has evolved continuously. The average velocity was one of the first parameters to be used. Once it became clear that this was insufficient for an accurate emission prediction, a power variable, like average acceleration was added. More and more parameters, like trip fraction of idling, were added, and eventually there was a list of over fifty parameters for each trip, from which the relevant ones were selected, by checking for the dependencies. For every vehicle category and emission component this process was repeated. Therefore, generating the emission model VERSIT+ had become a cumbersome process.

3 - TRIP PARAMETERS VERSUS INSTANTANEOUS PARAMETERS

The trip parameters are only valid for a trip, which consist of at least several hundred meters of driving, from stop to stop. This was also closely tied to the measurement data, which yielded a total emission in grams per test, for a particular driving cycle or trip. The actual time-dependence of the emissions, as the result of driving at that moment, or a few seconds before, has become available only in the last ten years with modal mass, or time-dependent, measurements. The quality of such data in the laboratory has increased in the last years. Hence it is possible to construct a second-by-second model from the data. However, two effects are important. First, the emission at a certain moment does not solely depend on the state of the vehicle at that moment. Typically, for the engine the operation up to eight to ten seconds back may influence the emission. For after-treatment, this time scale is much larger, several minutes for the temperature of the after-treatment, to days for the state of a DPF. On top of that, the aging of after-treatment systems, such as the nowadays ubiquitous oxidation catalysts, yield additional variation in the emissions in the same vehicle model.

Second, the driving behaviour is not just the velocity and acceleration at a particular time. An example is idling. During idling for minutes or longer the temperature of the engine and exhaust gases may drop, yielding typically larger emissions, than the emissions during ten or twenty seconds idling, while in front of a red traffic light. The latter form of idling is considered part urban driving, while the former idling has been investigated in special studies concerned starting the car, or the effect on the emissions of turning off the engine while waiting in a line for an open bridge, which is a typical Dutch problem.

The modal mass data is available in much larger quantities; hundreds of seconds per test, while only one value per test is given for bag data. The exception is particulate matter: still only one filter, in the standard method, per test is used, and only bag data is available. The filter results are correlated with alternative methods for second-by-second measurements like particle number methods, as PMP and CPC.

Although, second-by-second measurements and the corresponding instantaneous models, as function of velocity and acceleration, have their drawbacks, their advantages are significant. Proper care must be taken to still associate the velocity and the acceleration used with the driving behaviour under consideration. Such as a combination of idling and driving at moderate speeds, which are both elements of typical urban driving.

4 - VELOCITY AND ACCELERATION DEPENDENCE

A great part of the transition of VERSIT+ to the new version is to translate the bag results into velocity-acceleration dependent results. The aggregated data per trip makes a full conversion impossible, and from velocities and accelerations combinations have be sought, to construct a robust emission model.

Since for each vehicle category between fifteen and twenty five different drive cycles were used in the testing, the emission model can never have more than these fifteen to twenty five degrees of freedom. For example, if the velocity acceleration space would be divided in segments, it would yield a three-by-five checkers board. Therefore, it is important to choose the degrees of freedom in the emission model appropriately. In a sense, instead of relying on a long list of variables, or models, to find the most appropriate ones, the basic model is selected in advance.

Two criteria were used to select the model variables: First, the variables have to be independent to avoid the use of two variables which describe the same effect. Second, the variables have to be relevant to evenly divide the variables such that their share in the total emission is of the same magnitude.

The first criterion led to the introduction of the dynamic variable *w*. Emissions typically increase with acceleration and with velocity. Hence is the velocity decreases and the acceleration increases appropriately the emission will stay the same. The emission model may not depend at all of that combination of acceleration and velocity. This is the idealized situation. In practice the emission will vary slowly along this line, depending on the vehicle technology and emission type. But the slow variation can be captured in a limited number of degrees of freedom. The dynamic variable *w* is defined as:

$$w = a + 0.014v$$

where the acceleration *a* is in m/s^2, and *v* is in km/h. The data will general be in second-by-second data, the acceleration will be defined as the backward difference:

$$a_i = \frac{v_i - v_{i-1}}{3.6}$$

The consistency in this choice is more important than the exact definition. The emissions are not truly instantaneous, therefore, great effort to make the variables so would be superfluous.

The dynamic variable w describes the line (*w* = constant) along which the emissions are expected to vary only slowly. Hence, the remaining dependence, in terms of the velocity may be set in three categories, typical for the Dutch conditions, of urban, rural, and motorway driving: ($v \leq 50$ km/h, 50 km/h $< v \leq 80$ km/h, $v > 80$ km/h). Although in each of the cases, of urban, rural, and motorway driving other velocities than typical for that category will occur.

The second condition determines in which general regions the dynamic variable has to be divided. A low dynamic variable, $w < 1.5$, occurs the most, but the emissions for these values are also typically low. Hence, the frequency of occurrences of certain values of w multiplied by the emissions at these values yield the share in the total emission, under average circumstances. The three domains are set for velocities below 80 km/h at ($w < 0$, $0 < w < 1$, $w > 1$), for velocities above 80 km/h the low dynamic variable occur less, and the regions are set at ($w < 0.5$, $0 < w < 1.5$, $w > 1.5$).

Idling is set apart, by a region with $v < 5$ km/h and $a < 0.5$ m/s^2. The velocity and acceleration fall into ten regions. For idling and $w < 0$ the emissions are assumed to be constant in gram per second. In the regions $0<w$ the emissions are assumed to depend linearly with *w*. The model is now a simple function of velocity and dynamics, where the hard part is the appropriate determination of the coefficients in each of the regions in velocity-acceleration space. The emissions EM in gram per second are given by:

$$v < 5, a < 0.5 : EM = u_0$$

$$v < 50 : EM = u_1 + u_2 w_+ + u_3 (w-1)_+$$

$$50 < v < 80: EM = u_4 + u_5 w_+ + u_6 (w-1)_+$$

$$80 < v: EM = u_7 + u_8 (w-0.5)_+ + u_9 (w-1.5)_+$$

where the function $(..)_+$ yields $(x)_+ = 0$ for $x < 0$, and $(x)_+ = x$ for $x > 0$. The coefficients u_i form the core of the emission model.

The linear model of the emission EM allows one to use it both for second-by-second instantaneous emissions, and for the sum emission for a whole test. The driving behaviour in the driving cycle can be expressed by the ten variables dual to the emission variables $u_0, u_1, \ldots, u_8, u_9$: q_0 (number of seconds idling), q_1 (number of seconds at a speed lower than 50 km/h), q_2 (the sum of all w_+ values), etc. These variables are loosely named: *idling-time, urban-time, urban-dynamic, urban-aggressive, rural-time, rural-dynamic, rural-aggressive, motorway-time, motorway-dynamic,* and *motorway-aggressive*.

The emission from a test is the dot-product of $\mathbf{u}_{vehicle}$ and $\mathbf{q}_{driving}$:

$$EM_{test}[g] = q^T_{driving}[s] \cdot u_{vehicle}[g/s]$$

For the emission factor in g/km this results should be divided by the number of kilometres in a test:

$$EF[g/km] = \frac{EM[g]}{dist[km]}$$

The linear dependence of the emission with w in each of the regions will limit the effect of the velocity sampling and calculation of the acceleration. For example, if the velocity is sampled with 1Hz in 0.1 m/s accuracy, the acceleration can only be determined with a limited accuracy of 0.1 m/s^2. However, in successive contributions to the emission predictions in the same region, the sampling effects are properly averaged over, to second order accuracy.

This dependence on v and w in the emission model is based on a variety of fits of all kind of modal mass data from Euro 1 to Euro 4. It is a global fit, where the model 10 parameters u_i, allow the variation with emission type and vehicle categories. The highly nonlinear behaviour of the emissions with the increasing dynamic variable w, can be accommodated for in a segmented model: high emissions for high dynamics are unrelated to the prediction of low emissions at low dynamics. In the previous version of VERSIT+, nonlinearities of the emissions with variations of the trip parameters led to emissions beyond the bounds of the model, which had to be truncated. The new version does not require such bounds: the new VERSIT+ model is robust by construction.

Moreover, the use of the log-transformation, to limit the emission predictions to positive values, is abandoned. The unwanted effect of log-transformation is a model focus away from the high emissions toward the low emissions. In the interest of using and predicting the averages throughout the process, as will be shown later, the model uses the non-transformed values.

5 - HANDLING LARGE VARIATIONS IN MEASUREMENTS

Especially for CO and HC emissions only a small fraction of the vehicles, in a small fraction of the traffic situations, produce the majority of the emissions. Only for CO2, and in lesser extent for PM10 in certain older diesel vehicle technologies, the variation is smaller than the average itself. In all other relevant emission components, the variation inside the same vehicle class is significant. Therefore, emission modelling for a fleet and a wide range of traffic situations requires statistical analysis. Only a few measurements on a few vehicles are insufficient produce a representative national emission model. Several dozens of vehicles are required to produce enough statistics to bring the model uncertainty down to an acceptable value, less than 10 % of the mean emissions.

The distinction of the effects of driving behaviour on the emissions is even harder to archive. With a limited number of driving cycles the same limited number of driving situations or driving parameters can be separated. With the previous version of VERSIT+ this process became highly relevant, with the introduction of new driving categories, such as driving behaviour on the motorway with an 80 km/h speed limit with distinction between enforcement levels.

Two main changes are implemented in the current version. First, the driving behaviour is described by velocity-dynamics variables v and w. Second, each vehicle-fuel combination (some vehicles are tested on both gasoline and LPG) is analyzed separately for the emission differences between driving cycles. In this manner the vehicle and driving dependence of the emissions can be separated. However, some care must be taken to make this separation. Due to the large variation in magnitude, and the occurrence of many small measurement values in the tests, relative numbers are inappropriate. Instead, the average gram per second emission, of all the tests combined for a single vehicle, with the corresponding reference driving behaviour is the baseline value from which absolute changes for the different driving behaviours are determined:

$$EM_{\Delta DC}[g/s] = EM_{test}[g/s] - EM_{average}[g/s]$$

which is correlated with the change in driving behaviour:

$$\Delta DC = DC_{test} - DC_{average}$$

The driving behaviour DC are represented by the standard ten variables **q** = $q_0, q_1, ..., q_8, q_9$. The changes in emission, due to the changes in driving behaviour, are collected for all vehicles in the same category. With the use of the least-square fit for these categories, the emission dependence with driving behaviour is determined, yielding the ten coefficients **u** = $u_0, u_1, ..., u_8, u_9$.

There are several subtleties in this fitting process. First, not for all vehicle categories, all the ten parameters q_i for driving behaviour are varied independently, due to limitations in testing. Especially for motorway there is little distinction in degrees of sportive driving in the tests. Consequently, the matrix inversion, part of the least-square fit algorithm may be singular, or near singular. In the process only directions in which driving behaviour vary independently are included, by selecting the eigenvectors of the matrix associated with sufficiently large eigenvalues, indicating substantial variation in driving behaviour. The other eigenvalues are set to zero and a generalized inverse is used, avoiding uncontrolled variations in the coefficients. The eigenvectors are combinations of driving behaviour vectors **q**.

Second, the two results: the average emission for the average driving behaviour for a category, a direct result from the measurements, and the variation of the emission with a variation in driving behaviour, from the least-square fit, are to be combined in the set coefficients $u_0, u_1, ..., u_8, u_9$. For vanishing driving behaviour **q** = 0, the emissions should vanish as well. This is not naturally satisfied, since the emission results are pinned down at the average value, rather than EM(**q** = 0) = 0. Basically, emissions independent of driving behaviour will not appear in the variation, but only in the mean. Therefore, this part is added by hand to the coefficients $u_0, u_1, u_4,$ and u_7, which are the fractions driving at different velocities. This is done in such a way that the average emission for the average driving behaviour does not change. From the variation over the tests we find the driving behaviour dependence:

$$EM - EM_{average} = \bar{u}_0 \cdot (q_0 - q_{0,average}) + \bar{u}_1 \cdot (q_1 - q_{1,average}) + ... + \bar{u}_9 \cdot (q_9 - q_{9,average})$$

which should lead to an emission model, where emission are the result of driving behaviour only, i.e., no driving or idling (***q***=0) means no emissions:

$$EM_{model} = u_0 \cdot q_0 + u_1 \cdot q_1 + ... + u_9 \cdot q_9$$

with the global measurement result as constraint:

$$EM_{model,average} = u_0 \cdot q_{0,average} + u_1 \cdot q_{1,average} + ... + u_9 \cdot q_{9,average}$$

which is easily archived since the total time is $q_0+q_1+q_4+q_7$:

$$u_0 = \bar{u}_0 + \Delta$$

$$u_1 = \bar{u}_1 + \Delta$$

$$u_4 = \bar{u}_4 + \Delta$$

$$u_7 = \bar{u}_7 + \Delta$$

where $\Delta = \dfrac{EM_{model,average} - (u_0 \cdot q_{0,average} + u_1 \cdot q_{1,average} + ... + u_9 \cdot q_{9,average})}{q_0 + q_1 + q_4 + q_7}$

Finally, little less than half the emissions tests are type-approval tests such as the MVEG-A, MVEG-B, and FTP tests, which are less representative for real world driving. To ensure that these tests do not dominate the analysis, a weighted average of the type-approval tests and the real-world driving tests has been used during the model development. The weighting of type-approval test results is one fifth of the real-world test results.

6 - HISTORY EFFECTS AND MODAL MASS DATA

The most important history effect is cold start. Most of the CO and HC emissions are produced just after the start. Also the CO2 emission is typically higher during the cold start. The retention of the cold start effects depend on the components, but in VERSIT+ the time-dependence is not taken into account, mainly because it is hard to determine the precise trip in average Dutch driving. It is simpler to assume that in the majority of the cases the engine is warm at the end of the trip, meaning that the full contribution of the cold start emissions were produced during the trip. Depending on the components this may be after less than hundred meters for HC and CO to four to five kilometres for CO2 emissions and emissions related to the higher fuel consumption.

Modal mass, or second-by-second, data can be treated in the similar manner in the VERSIT+ model as bag data. The prediction of the model depends on the ten parameters $q_0 ... q_9$, which are known for every second. In principle the measurement of every data point counts as a separate test. Some care must be taken, in this case unlike the bag data, to compensate for history effects. The emission may have a delay by some time with respect to the velocity and acceleration.

At TNO modal mass data has be measured intermittently from 1998, during the tests. Some of the older data exhibit misalignment: the CO2 signal does not coincide with the power demand as determined from velocity and acceleration, but is advanced or delayed with respect with the power demand. Likewise, all other signals are misaligned. Possibly, the delay may vary with exhaust gas velocity. Modal mass data must be analyzed both for history and misalignment effects.

Investigations are underway to incorporate both the older and the new modal mass data with a proper weighting, with respect to the test, or bag, data now present in the VERSIT+ model. The higher time resolution will yield more accurate data, however, only for a single vehicle. This size of this data, every second a separate data point, must not swamp the variation over vehicles and maintenance states, from bag data, core to the VERSIT+ analysis.

Figure 1: The two elements of the emission model coming together: the average driving behaviour and the corresponding average emission, and the variation in the emission with the variation in driving. Only two of the ten q_i axes are depicted.

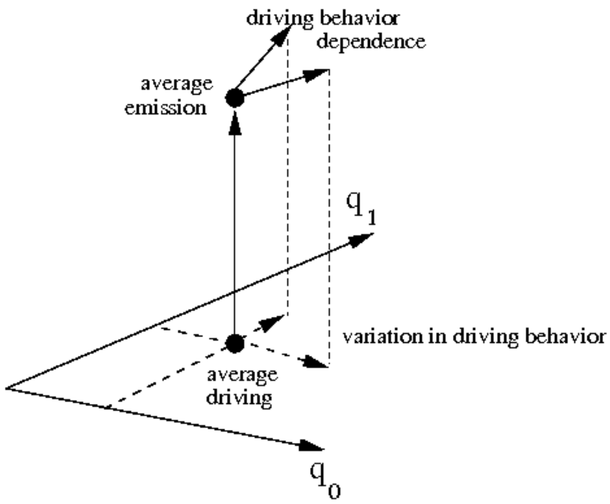

Figure 2: The NOx emissions for the Euro-3 petrol vehicles on the Dutch motorway F&E cycles: left the data as is, right the data relative to the average emission of each vehicle independently, showing clustering of the data. The averages are indicated by the circles.

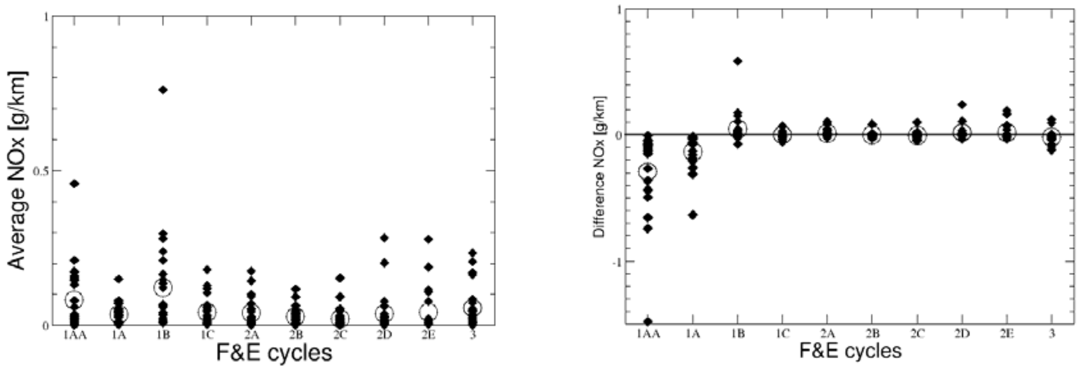

Figure 3: Sketch of the generic piece-wise linear model dependence of the emissions on the velocity-acceleration regions.

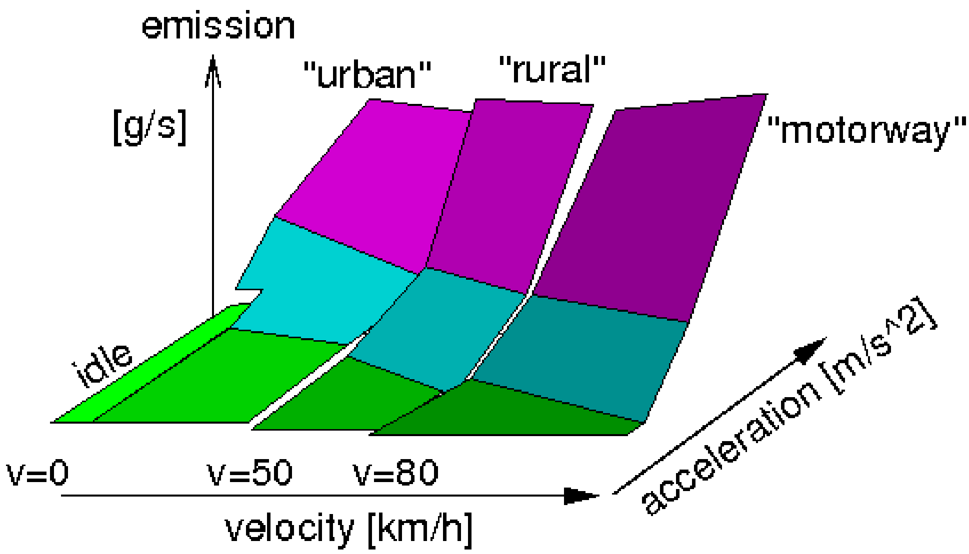

Table 1: The proposed emission factors for average over passenger cars, two-wheelers, and light commercial vehicles with VERSIT+3 for 2010.

	urban				
	congested	medium	free flow	rural	motorway
NOx [g/km]	0.68	0.44	0.48	0.27	0.26
NO2 [g/km]	0.22	0.14	0.15	0.08	0.10
PM [g/km]	0.045	0.039	0.039	0.014	0.020

7 - CONCLUSIONS

Road traffic emissions are an interplay between vehicle technology, vehicle state, and driving behaviour. For a proper emission model the variations in all three must be covered. The Dutch in-use compliance program does so. With over three thousand measured vehicles, the present day fleet composition on the Dutch roads is covered sufficiently. Second, besides the NEDC cycle several real-world driving cycles, such as CADC, OSCAR, and special Dutch real-world driving cycles are used in the tests, which cover a large range of driving behaviour. For the state of the vehicle, the sample of vehicles is expected to cover the variation in maintenance states. However, detailed knowledge of the state of the after-treatment systems is under investigation, to assess their interaction with driving behaviour and their particular influence on emissions.

The recent developments to the VERSIT+ emission model are tuned toward decoupling the aspects in the emission estimation. First, the decomposition of vehicle technology and driving behaviour is the central elements to improvement of the statistical approach. Second, the driving parameters closely related to velocity and acceleration separate the instances of high emission from the instances of low emission. The combination of both aspects allow the full usage of all available measurement data, including the previously deemed inappropriate NEDC test data, for real world driving.

Due to the improvement in the VERSIT+ modelling approach, the model is now tuned toward the future. The model enables the consistent calculation of road traffic emissions for a wide range of different real world conditions. Accurate emission factors for national emission inventories can be calculated, but also the effect on the local emissions due to traffic measures can be evaluated. In addition, the model enables the use of both modal mass measurement data and the older bag data.. Furthermore, the model is geared up to investigate and incorporate separate after-treatment modules.

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