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TNO report

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Uncertainties in emissions of road traffic: Euro-4 diesel NO_x emissions as case study

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Contents

1 Introduction

1.1 General

Increasingly, there is the demand that figures for environmental policy are given a measure for the uncertainty. This requirement also holds for emission totals of pollutants due to the road traffic by vehicles. The computation of the emission total of a given pollutant contains several ingredients: the emission behavior of individual vehicles, the driving behavior of the vehicles and the total distance travelled. This will be discussed in detail below. Each step in this computation carries an uncertainty. An analysis of the accumulated uncertainty in the process of determining total emissions of pollutants is the topic of this report.

The research is carried out for the “Emissieregistratie” project: the national emission inventory programme to determine the annual total emissions. Road traffic is a major contributor in certain emissions at a national level, like NO_x. The results, however, will also be useful for the air-quality models: part of the SRM1 and SRM2 (“standaard Rekenmethode”), to estimate the bandwidth in the air-quality predictions.

The approach described in this report treats the derivation of the emission factors from the emission data as a white box process: each variation in the input is examined, and carried through the whole process from emission data to emission factors. The report deals with a major contributor of NO_x emission: the Euro-4 diesel passenger cars. The drawbacks for the emission modelling for Euro-4 and earlier were recognized in 2009. Since then three major improvements have been implemented: the use of second-by-second test data, the systematic measurement of NO_2 for air-quality, and the selection of vehicles no longer random, but a coverage of the total fleet on the basis of sales figures.

1.2 Generic probabilities in emission testing

Overall, emission tests have been reproducible within a few percent, on the same vehicle and the same test. The equipment is certified for the official type-approval testing. Different vehicles of the same make and model, and mileage, have also nearly identical test results, if the maintenance states are proper. With the latest after-treatment technology, this is no longer the case, as regenerations of a filter or buffering catalyst, may or may not occur in a particular test. In type-approval testing this is excluded, in the test programme for emission factors it is weighted over.

The vehicles are tested “as is”, in a proper maintenance state. Lately, the most common error is due to the chassis dynamometer test itself. Since one axle is standing still, the engine control may generate an error based on inconsistent vehicle state data. Such errors are corrected, but complicate the test programme. Two parts of vehicle emissions are covered only limitedly by the test programme. They may require separate investigations: The first one is deterioration with age and mileage. The tested vehicles are typically around 20 000-30 000 kilometres driven before testing. Hence they are still relatively new: in the second year. Additional deterioration is assumed from separate tests.

The second limitation is technology failure and tampering with the vehicle. EGR valves may be fixed, aftertreatment components can be removed. It will occur in a limited number of cases, but the consequences are still significant, due to much higher emissions associated with such malfunctioning emission control.

Large variation occurs between different vehicles and models. Also the test cycle, i.e. driving behavior, affects the results substantially.

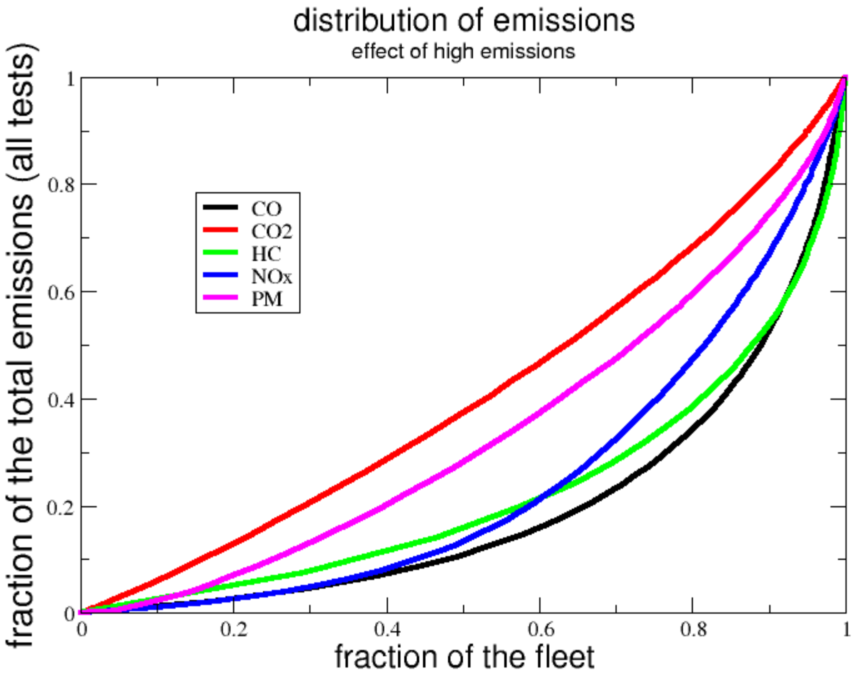

Figure 1 The average test results show that a few vehicles are responsible for the major part of the emission for HC and CO. As a rule of thumb 10% of the vehicles are responsible for 40% of these emissions. The CO2 is more proportionally distributed, NOx and PM emissions are intermediate cases. This includes more than ten thousand tests in the national test programme.

Vehicle emissions are more and more associated with failures and incidences. Typical HC emissions are due to an occasional misfiring of the combustions, for example, at a sudden decrease in engine load. Likewise, NO_x emissions are more likely to occur in transient load change on the engine. The typical emission profile has a larger spread than the average, due to a shorter or longer tail of high emissions. For the test average results this already yields a spread in outcome. See Figure 1. However, for a single test, the variation is much larger. See Figure 2 and Figure 3 for results per test for different Euro-5 diesel vehicles.

In the case of a road-side measurement, only a short moment is captured, which may lead to a large variation in measured emissions for even the same individual vehicle. Claims made by remote emission sensing (RES), or road-side measurements, on high-emitters and test averages are often overly optimistic. If the same analyses are performed on second-by-second data from the laboratory, the variation in the instantaneous results, such as uncovered by road-side measurements is large (Kraan et al., 2012).

Apart from the absence of equipment to measure particulate matter properly, as well as a NO_2 sensor in road-side measurements, the RES measured emissions occur in incidences. The absence of appropriate sensors is (tried to be) compensated by additional modeling, introducing artificial consistency in the results. The erratic emissions over time cannot be compensated for. Hence missing or catching such an incidence in the remote emission sensing will qualify or disqualify only the short time behavior of the vehicle, rather than its overall performance. Furthermore, different aftertreatment technologies have different relations between NO_x and CO_2 emissions, which ratio is measured by remote sensing. For example, SCR trucks typically have the highest NO_x/CO_2 ratio while idling, but the contribution of idling to the sum NO_x emission is negligible. If only the ratio is measured, the distinction in engine operation cannot be made and idling emissions are overrated.

As a rule of thumb, at TNO in the test program on the chassis dynamometer at least ten vehicles per technology or vehicle category and 40 minutes or more testing per vehicle are required to cover the variations and incidences of the emissions in the test.

Before 2009 only bag data, or overall test results, was acquired in TNO laboratory emission tests. This puts a severe restriction on the amount of data needed to produce a proper emission factor. Since 2009 as a rule, second-by-second data is logged and calibrated with the bag data. The analysis described in this report determines the uncertainties of emission factors determined prior to 2009. This type of test data is used to determine all emission factors up to Euro-IV for heavy duty and Euro-4 for light duty. Except for a couple of special cases, like Euro-4 CNG and LPG vehicles, which were made in the transition period from bag data, to second-by-second or modal mass data. In modal mass data, driving behavior can be associated with the emissions directly, or causally.

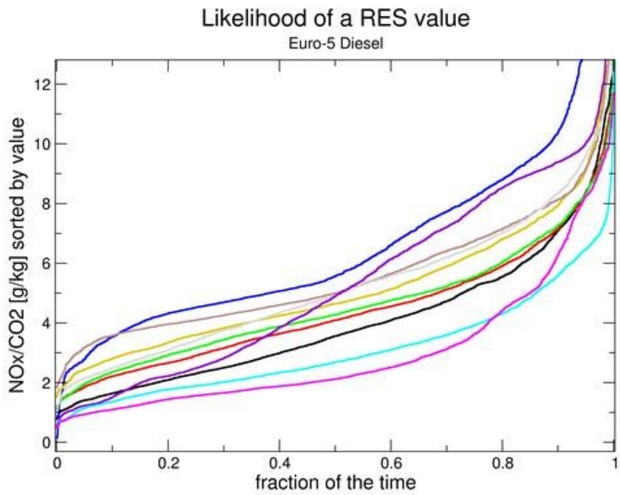

Figure 2 The sorted specific NO_x, or NO_x per CO_2 emissions, on the CADC test in the laboratory for different Euro-5 diesel vehicles. Only in a short part of the test the emissions are extremely high. The area under the curve is a measure of the total, or average, emission.

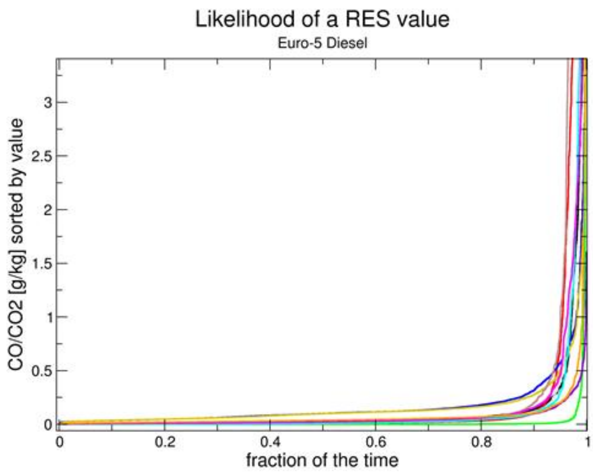

Figure 3 The specific CO emissions of Euro-5 diesel vehicles on the CADC test in the laboratory. In this case a short test will no longer provide an appropriate emission average, as the emissions occur only in a few instances.

Hence, the two variations in the emissions in the tests are, firstly, the test itself, minimized by long test cycles and standardized conditions, and secondly the variation between the different vehicles in the same vehicle category, like Euro-5 diesel passenger cars. Occasionally, different vehicles of the same make and model are tested. The variation of the results of the same make and model typically has the smallest spread.

The third variation, outside the range of testing, is the variation between specific tests and the corresponding road type and driving conditions.

In part it can be studied by using different test cycles of, e.g., urban driving. In particular the conditions on the road, in common usage, is difficult to study properly.

With Euro-5 testing of passenger cars, rather than a sample from the total vehicle fleet, the sales data of all vehicles is analysed (Ligterink, Van Mensch, and Kadijk, 2012) The number of vehicle models, on sale in a particular year, is in the order of ten thousand. The most common models, with large sales numbers are a few hundred. Investigating the engines used in these most common models revealed that only eleven different engines are used in more than 50% of all the diesel Euro-5 vehicles sold. Developing a modern engine is major effort, which explains the dominance of certain engine models. For each of these dominant engines some engine calibration per particular vehicle model is expected, but in the basis the engines remain the same. Hence the different manufacturers collaborate in engine development, and the same engines are used across different models and brands. In this approach, the largest variation in emission results is removed from the emission testing, by covering the sales explicitly. With 11 vehicle models, about 25% of the model sales, and over 50% of the engines sales, in The Netherlands is covered by the TNO test programme.

The current study does not cover the test length, as it is based on the older test data, which consists solely of bag data, i.e., a single test result and not second-by-second data. Furthermore, it is not sales weighted approaches, but the traditional approach of a random sample of test vehicles from the Dutch fleet and test results, combined with the methodology of the TNO emission modelling in VERSIT+. The uncertainty is derived from the the variation of the results with the variation of the sample.

1.3 Measure for the uncertainty

A good measure for the uncertainty in a measurement or a parameter calculated from measurements is the size of the confidence window that contains the true value with a certain high probability. The uncertainty U is then defined as the statistical spread of the number (half the width of the confidence window) divided by the expected value or mean of the actual number.
Hence, for a measurement or parameter with normally distributed random errors the 95 % confidence uncertainty reads:

$$U = \frac{2\sigma_x}{\bar{x}}$$

By definition, the uncertainty is a relative number, which we will express as a percentage (by multiplying the above U by 100 %). To give an order of magnitude: in (PBL, 2012) the uncertainty for the NO_x emission due to the combustion of fossil fuels is characterized as 50-100%.

1.4 The various steps in the computation of the total emission

In the VERSIT+ model, the computation of the total emission is a three steps' process. First, there is the model for the emission behavior of an individual vehicle. This is described by the emission map. The emission map is a piecewise linear function in the speed-acceleration domain. There are 10 parameters describing the functional behavior of the linear pieces.

These 10 numbers are summarized in a 10-parameter vector u. This emission map is derived from a set of results of bag data for various vehicles using a least squares algorithm. The emission factor is then computed as

$$EF = u \, . \, q$$

See (Ligterink and De Lange, 2009) for details. The q-vector in this expression is a 10-parameter vector derived out of the speed-acceleration time profile. Loosely formulated, it contains the time spent in various dynamical regimes, weighted with the dynamics for some components of the vector. The speed-acceleration time profile of some trips that are considered representative are used to derive a q-vector. The q-vector is then divided by the trip length so that an emission factor is obtained if the q-vector is inserted in the piecewise linear model. This processing of the driving behavior is the second step. Finally, the mean emission factor $\widehat{EF}$ must be multiplied with the total distance travelled by all vehicles together, l, to obtain an estimator for the total emission

$$\widehat{EM} = EF \;\, l$$

It should be noted that the total emission is approximated as a product of three aggregates: an emission model for the average vehicle times the driving behavior of an average person times the total driving distance. This average is then an approximation of the sum over all vehicles of the product of the vehicle's own emission behavior times its own driving behavior times the distance travelled with that vehicle,

$$EM = \sum_v u_v . \, q_v l_v \approx \hat{u} . \hat{q} \; l$$

Here, the summation runs over all vehicles v. However, the reduction to a product of three averages is a simplification as correlations between the variations from the mean are not considered.

The uncertainty for the total emission is an accumulated uncertainty of the uncertainties in the three steps.
First, there is the uncertainty of the emission map of an individual vehicle. In the derivation of the emission map, only a limited number of vehicles is used: it is a finite sample. This causes an uncertainty related to the sampling variance. (The final answer depends on the sample the calculation is based on. As the sample could have been different, also the final answer could have been different. This gives a spread.)
Second, there is the uncertainty in the driving behavior: there is some arbitrariness in what speed-acceleration profile is used to evaluate the emission map. To assess the uncertainty of this step, one can perform a sensitivity analysis by varying the speed profile used. The uncertainties in the first two steps can also be computed by determining the uncertainty in the emission factor for a mean given driving behavior taken together with the uncertainty due to varying driving behavior.
Third, there is an uncertainty in the total distance travelled per vehicle category.

The emission total is the product of the emission map, the driving behavior and the distance travelled. To find the total uncertainty, we then have to add the three relative uncertainties as a propagated error.

The total uncertainty is obtained by the methods of error theory for multiplication as the square root of the summed squared relative errors, so that the total relative uncertainty reads as

$$U = \sqrt{U_{EF}^2 + U_q^2 + U_l^2} \tag{1}$$

Here and throughout the analysis, we assume normal distributions of the errors in measured quantities. We will perform the uncertainty analysis for the emission factor for motorway driving, as most kilometers are driven there.

2 Uncertainty in emission factor due to mixed vehicle population

The first step in the determination of the total emission, as introduced in the previous chapter, is the emission model for a single vehicle. In VERSIT+ there is an emission map for each separate VERSIT+ vehicle class , describing the behavior of an average car in that category.
As described above, the emission map is determined by performing a least squares fit to a set of bag data. This set of bag data is a very small sample of the entire vehicle population for that particular VERSIT+ vehicle class. If all cars had been measured, there would be no uncertainty in this step . The mean emission factor for a VERSIT_+ category, can then be estimated by multiplying this estimate for the mean emission map with the mean driving behavior (q-vector). The variance of this estimator gives a measure for the uncertainty of this emission factor.

To assess the uncertainties around the bag result, we perform a jackknife algorithm (Efron, 1982). The jackknife algorithm is a resampling technique, based on the assumption that each element of the sample had the same probability to enter the sample and the same probability of being an outlier. The jackknife estimator for the variance is the variance over all various subsamples with consecutively one element of the original sample left out. Each subsample thus obtained has the same probability of being a valid representative sample of dimension one less than the actual sample. Therefore, the jackknife variance is a good estimator of the variance due to the finite sample.

For an application in our situation, we have to assume that all vehicles in the measurement data had the same probability of entering it. If this is not the case and some vehicles have been chosen on purpose for the case of being interesting that may have deviating behavior, the jackknife variance estimator may give an overestimation of the variance.

In our situation, we took the set of bag data. We stratified the measurements into VERSIT+ categories. Per VERSIT+ category, we consecutively left one car out and computed the emission map and subsequently the motorway emission factor by the method described before. Then, with the i-th car left out, we get a set of emission map parameters

$$u_i$$

And for this subset the emission factor obtained if only this subset would have been available is denoted

$$EF_i = u_i . q.$$

Here, q is the mean motorway driving behavior. The variance over all subsamples (each with one car left out) gives a measure for the variance of the mean as an estimator for the population mean

$$\hat{\sigma}_{JACK} = \left(\frac{n-1}{n} \sum_{i=1}^{n} \left(EF_i - EF_{(.)} \right)^2 \right)^{1/2}$$

The mean of the u_i is denoted $EF_{(.)}$.
The uncertainty of the emission factor is then defined as

$$U_{EF} = \frac{\hat{\sigma}_{JACK}}{EF},$$

which we will express as a percentage. The results for the NO_x emission factor for motorway for 4 VERSIT+ classes of Euro-4 passenger cars are summarized in Table 1 below. They are the most contribution to the light-duty NOx emissions prior to 2010.

Table 1 Jackknife uncertainties for various VERSIT+ categories

VERSIT class	EF_{WT3} (g/km)	$\hat{\sigma}_{JACK}$ (g/km)	U_{EF} (%)
LPABEUR4A	0.0196	0.0122	63
LPABEUR4M	0.0101	0.0106	97
LPADEUR4ADDI	0.3567	0.1762	49
LPADEUR4MDDI	0.4351	0.3476	80

Concluding this subsection, we note three things. In the initial stage of the research, we have tried to compute the variance due to a mixed vehicle population with a bootstrap method. Because of the very lengthy computing time, we have not pursued this further. We also have applied the jackknife procedure on the experiment level. We thought it to be more correct to perform it at the vehicle level, thus assuming that the set of measurement data is a representative sample at the vehicle level (so multiple measurements on the same vehicle only count as one).

We had to use a jackknife approximation to the variance instead of an ordinary standard deviation because of the more involved way the piecewise linear model for the emission map depends on the sample.

3 Uncertainty in emission factor due to varying driving behavior

As discussed before, the second step in the computation of the total emission is the driving behavior. Because we consider only a limited time interval instead of all driving time, this too introduces a sampling uncertainty.

To find a measure for this uncertainty due to the fact that only a limited time window is taken, we make a sensitivity analysis. We make this analysis for the motorway driving. The motorway emission factor for several motorway drive cycles (each summarized into the q-vector q_j, where j indexes the various cycles) were determined as

$$EF_j = u.q_j \quad ,$$

the emission factor corresponding to the j-th variant of the motorway drive cycle. Defining the mean of all various emission factors for these various drive cycles as

$$\overline{EF} = \frac{1}{n}\sum_{j=1}^{n} EF_j \ ,$$

then the corresponding standard deviation follows as

$$\hat{\sigma}_q = \left(\frac{1}{n-1}\sum_{j=1}^{n}\left(\overline{EF} - EF_j\right)^2\right)^{1/2}.$$

This standard deviation is a measure for the spread due to the uncertainty caused by the limited time window.
In our sensitivity analysis, we have varied the motorway drive cycle by taking for it the different Dutch motorway cycles (for 80 – 120 km/h speed limits) and the motorway phase of the CADC cycle (130 km/h version). The results for the motorway NO_x emission are summarized in Table 2 below.

Table 2 Emission factors and uncertainties due to uncertainty in driving behavior

VERSIT+ class	$EF_{motorway}$ (g/km)	σ_q	U_q(%)
LPAPEUR4A	0.0163	0.0042	26
LPAPEUR4M	0.0165	0.0037	22
LPADEUR4ADDI	0.4516	0.0257	6
LPADEUR4MDDI	0.4230	0.2113	50

The relatively low value for the uncertainty for LPADEUR4ADDI is due to the strange emission map obtained after the SVD. In our modeling it turned out not to be positive definite, which is unphysical. This is repaired when emission predictions were made.

The calculation of the variance for q should be weighted by a certain representative number of vehicle kilometers per drive cycle.
As it stands, the give uncertainties are overestimations: as it is assumed that the number of kilometers for all motorway traffic situations (as represented by the various drive cycles) is the same.

4 Uncertainty due to margin in vehicle kilometers

The last step in the computation of the total emission is the multiplication of the emission factor with the total number of kilometers driven. Traffic performance expressed as vehicle kilometers is determined by the government, however, not at the deep aggregation level of individual VERSIT+ categories. We therefore have to make an estimation of the number of kilometers for a vehicle class on a deep level of stratification out of the total traffic performance. This is done as follows. We assume the relative number of kilometers for a given vehicle class to be proportional to the relative fraction of this vehicle class in a fleet decomposition. Such fleet decompositions have been made when license number investigations were performed. In such a study, at a given location during a certain time frame, the license plates of all vehicles that pass by are photographed. Using information from the traffic authorities, the legislation category and fuel type for the vehicle with this license plate, and by combining these, the VERSIT+ category can be obtained. Thus the relative occurrence of the various VERSIT+ categories is determined. Assuming that the location is representative for all driving behavior, the fraction of kilometers per vehicle category is equal to the relative occurrence. Taking the same point of view, the variance over various locations of the relative occurrence per category is a measure for the uncertainty of the vehicle kilometers per category. In these license plate investigations, forecasts for later years are made. When combining the results of license plate studies in Amsterdam, Rotterdam and Utrecht and taking the forecast for 2015 thereof, we find the following relative occurrences, standard deviations and uncertainties for the vehicle kilometers as given in Table 3 below.

Table 3 Relative occurrence of vehicle categories and uncertainties caused

VERSIT+ class	*Relative occurrence(%)*	*σ (%)*	*U* (%)
LPABEUR4	12.7	1.93	15
LPADEUR4	3.04	2.39	78
LPADEUR4DPF	3.89	2.63	67

5 Accumulated uncertainty

In the previous sections the uncertainties arising in the various steps, that together form the computation of the total emission, have been determined. The total uncertainty is the propagated error of all errors. It is computed as the square root of the sum of squared relative uncertainties in the various steps.

In this section we compute the total relative uncertainty. To this end, we use Eq. (1).

We then get the following results for the uncertainties:

Table 4 Accumulated uncertainty for EURO4 vehicle supercategories

VERSIT superclass	$U(\%)$
EURO4 petrol automatic transmission	70
EURO4 petrol manual transmission	100
EURO4 diesel automatic transmission	92
EURO4 diesel manual transmission	122
EURO4 diesel DPF automatic transmission	83
EURO4 diesel DPF manual transmission	116

So we conclude that for the NO_x emissions on the motorway, the uncertainty is of the same magnitude as the emissions itself.

6 Conclusions

The jackknife approach, by taking selections of the input data, to determine the variations in the eventual emission factors as result of the different types of input and assumptions, yield a substantial bandwidth in the results. The 95% confidence interval lies at a 100% variation in the emission if all aspects are added.

This result holds for the approach for derivation of emission factors needed for testing prior to 2009 (up to Euro-4 passenger cars and Euro-IV trucks), where a single test result was available per test. Nowadays, time-series data is available, such that high emission results can be pinpointed to aspects of driving behavior. The number of vehicles test have decreased over the years, but the available data per test has increased. The new balance is unclear. However, the limited number of vehicles has led to innovative approaches to achieve a representative measurement program for emission factors.

Still, with new emission categories, Euro-5 and Euro-6, and the new test protocol, the uncertainties remain. With the Euro-5 the expected uncertainty in the NO_x emission remains at 15%, based on variations in vehicle fleet and tests (Ligterink, Van Mensch, and Kadijk, 2012). Note this 15% uncertainty does not include uncertainties for fleet composition and driving behavior. For Euro-6 the uncertainty is much larger, (Ligterink et al. 2013) as it is expected that the eventual dominating technology for Euro-6 diesel passenger cars is not yet fully settled, and it may depend on the effectiveness of European RDE (Real Driving Emission) legislations to detect systematic deviations between type-approval test results and limited effectiveness of the emission control technology on road. This legislation is due in 2017-2020.

The findings for Euro-4, with large uncertainties, are reason to make the ad-hoc improvements for Euro-5 and Euro-6 more systematic. It would involve the assignment of technology categories, or manufacturer groups, to parts in the total national mileage. Furthermore, the knowledge driving behavior is due for an update, as the results from 2004, on which standardized driving behavior is based, have reduced validity with the recent changes in infrastructure, traffic control, and speed limits.

7 Literature

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8 Signature

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