Dependence on technology, drivers, roads, and congestion of real-world vehicle fuel consumption

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Abstract

The Dutch national transport CO_2 emissions are determined by summing individual cases: a particular vehicle, on a particular road and traffic situation. In this paper the different aspects and the relations among them, as used in emission predictions, are outlined. In particular the central role that the CO_2 type-approval value (from the NEDC test) plays in the real-world CO_2 emissions since 2000 is clarified.

1 INTRODUCTION

Reducing CO_2 emissions, and thereby limiting global warming, requires substantial effort and resources. The effectiveness of the measures taken are not a priori clear, as many aspects influence the eventual outcome. In the attempts to arrive at accurate predictions of the total vehicle CO_2 emission in coming years, the complete picture must be unravelled. This paper gives an overview of many relevant aspects for current and future CO_2 emissions of passenger cars.

The total vehicle fuel consumption, and herewith the Tank-to-Wheel (TTW) CO_2 emission, has not dropped significantly, despite the general attention for sustainable mobility in the last decade. To link the total fuel usage to individual cases and specific causes requires data from many sources. This complexity is the manifold question: "who drives what, where, how, and when?" Furthermore, all this data has to be combined to determine dependencies.

If a vehicle uses more fuel over a certain distance than expected, this can be caused by any of numerous phenomena: The driver spends every day in traffic congestion, there might be a mechanical or electronic fault in the engine, a large portion of the distance can be traversed at great speed, or sportive in other manners, there might be a large weight in the vehicle, e.g., three passengers carpooling, The driver might drive in high gear, does only short trips with a cold engine, or keep the air-conditioning on a lot, etc.

Also, the implemented fuel-saving technology may fail to perform. Not in the least, based on the standard NEDC (Driving cycle used for the Type Approval) test, the expectation of fuel efficiency might be too high. This between real-world fuel consumption and the laboratory NEDC test results is increasing. The legislation based on the NEDC test seem to have improved the low-load part of real world engine usage, associated with low velocities, idling, stop-and-go traffic. However, a driver whose traverses mainly on the motorway will not benefit much from the fuel-efficiency improvements in the NEDC test, as this test has mainly a low velocity part related to urban and rural situations. See Figure 1.

Real world emission for pollutants (NO_x, CO, HC, and PM) has been a real concern from the 1980s. Since 1992 both the test protocol and the limit values have been adapted to yield results that carry over from the laboratory to real world. For example, the EUDC (Extra-urban Driving Cycling) was introduced to augment the original UDC (formerly ECE), Urban Driving Cycle, with higher velocity testing, to cover more of the actual driving. For fuel consumption, the consumption at 90 km/hr and 120km/hr constant velocity were available, but led to optimization of the motor management for these specific velocities.

The real-world circumstances, leading to an increase in fuel consumption have even a worse effect on the emission of pollutants, such as particulate matter and nitrogen oxides. In the total lifetime older vehicles have much higher emissions than modern ones. The effects of fleet renewal play a much more dominant role for pollutants than in CO_2 emissions. In an LCA the usage plays also a major role, next to the total mileages for particular vehicles and technology.

Our own research, employs fuel-card data, in-usage compliance programmes, traffic models, driving cycle development, interviews, and technology assessment, with the data from national and international sources, such as the national statistics bureau, scrappage programmes, MOT testing, the European Community, the UNFCC, etc., to arrive at a comprehensive view of the vehicle ownership, usage, road use, congestion times. This is the basis needed to perform assessments of effectiveness of new fuel-saving technology, congestion reduction, driver incentives, and government policies. In the predictions of emissions it is necessary to have a comprehensive, quantitative picture of the square: technology-driver-road-congestion and their effect on fuel consumption. (1) These four corners vehicle technology, road types, driving behaviour, and congestion are all needed to determine the actual emissions. Quite often only two of these four dependencies are known. Such partial studies will not recover all effects. For example, when a vehicle becomes older, its typical usage changes: more urban driving but less rush hour driving. More urban driving will increase the emission per kilometre, a reduced time spent during congestion decreases it, and a lower mileage will also decrease the contribution of older vehicles to the total emission.

2 COVERING THE CORNERS OF VEHICLE EMISSIONS

Road type, vehicle technology, driver behaviour, and congestion are the four factors of the emission, each with their own time scale and actors which may influence the effect. The driver has a large impact on the actual CO_2 emission, probably the largest. The gains in technology follow closely. The congestion is often expected to have a large impact too. However two effects are often neglected here: free flow attracts more traffic in the long run, and congestion is often over only a short distance with long times but limited number of kilometres driven. In the Netherlands the prognosis is that total distance travelled will increase by 7.5% between 2010 and 2015. The congestion reduction measures probably have a part in this. Road types have little effect, they are the premises for distinguishing categories of driving behaviour for different service levels. Also climate, wind, road surface, and inclination of roads are fixed for a location, but may vary from country to country. For example, driving behaviour in congestion on the motorway or congestion on the urban roads are very different.

2.1 Road types

Over a hundred combinations of road types with degrees of congestion are distinguished by emission modellers, in order to chart the European situation and accurately predict traffic emissions for each situation. The main distinction is urban, rural, and motorway. Driving behaviour information and traffic data is largely available for traffic in urban environment and to some extent for motorway conditions. Rural driving behaviour, with typical average velocities between 40 and 60 km/hr, is least well known. In physically based emission models, it is a troublesome case, which often leads to an underestimation of the rural emissions. The core of the problem lies in the functional velocity dependence in such models:

$$EF[g/km] = a/v + b + c.v + d.v^2$$

Consequently, the coefficients *a,b,c,* and *d* are fitted with emission tests, producing a good urban and motorway result, but generating a rather unnatural dip at intermediate velocities, because of the generic parabola shape. See Figure 1. At TNO, in the emission model Versit+, this is avoided by having independent fits of the three regimes, which yield higher rural emissions. (1) However, the actual driving in rural conditions is not very well known.

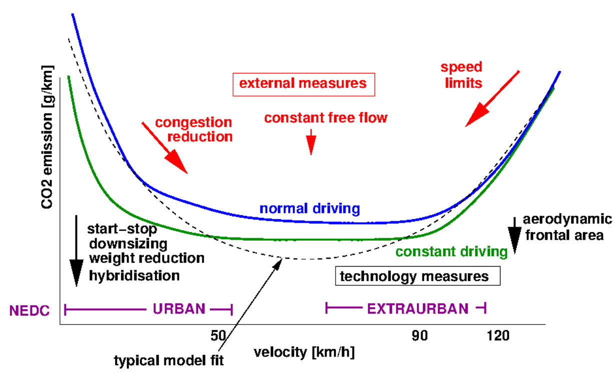

Figure 1 The CO2 emission as function of velocity alone. The regions of the NEDC test generate a focus low-velocity reduction. The typical flat minimum is not reproduced by the typical physical models fit.

Road types are not just the surface and junction, affecting roll resistance and stops per kilometre, but also the speed limit and enforcement categories. In the Netherlands there has been a recent discussion on introducing on specific motorways a speed limit of 130 km/h rather than one of 120 km/h, the maximum thus far. To provide a scientific basis for the discussion, TNO has derived a representative drive cycle for 130 km/h, from driving behaviour in the trial period. (2) We then observed that the emission behaviour at speeds slightly above 120 km/h was still well predicted by the model for the Dutch driving, which was developed for velocities up to 120 km/hr. The CO_2 emissions will increase with roughly 5% on 130 km/h stretches as compared to 120 km/h stretches, from this analysis. Note that a 120 km/h or a 130 km/h speed limit does not mean that the average vehicle velocity is directly related to the speed limit.

2.2 Vehicle technology

The Europe-wide approach to CO_2 reduction of transport focusses on the levers it has. These levers are mainly in the field of vehicle technology. Hence, the NEDC type-approval test cycle and vehicle technology are two sides of the same coin. The NEDC test is a technology neutral way of stimulating new technology, and, despite many criticism, it has been successful in doing so. In the period after 2000 somehow the weight increase and CO_2 emission remaining nearly constant has been turned around. Likewise, consumers seemed to have discovered the small but comfortable fuel-efficient cars.

2.2.1 Fuel and ignition types

Traditionally diesel technology was considered superior due to the higher efficiency. With the introduction of the three-way catalyst petrol was the cleaner, but less efficient alternative, and the choice was between "clean" and "efficient", sparking fierce debates. Downsizing the engine, thereby reducing the power-loss overhead in low-power engine output exists for both petrol and diesel vehicles, but most technologic engine improvements with a substantial CO_2 reduction has been for spark ignition vehicles since 2000. The difference between the two, in terms of CO_2 emission is no longer as large as it was ten years ago. However, due to the larger density of diesel, which weighs 830 grams per litre, against 745 grams per litre for petrol, the efficiency of a diesel vehicle in litre/100km is larger.

2.2.2 Hybridisation

A new trend is hybridisation. The use of a start-stop, or an electric booster engine, or forms of rerouting engine power, have little advantage in free flow traffic conditions on the motorway. In urban circumstances, or congestion, the hybridisation proves both its advantage in fuel efficiency and driver comfort. It is only speculating how much the stops and idling time of the NEDC test has contributed to the popularity of hybrid vehicles. However, on the NEDC test, and in particular on the UDC part the hybridisation proves superior.

2.2.3 Weight aspects

Weight is comfort, weight is safety. The historic weight classification to group passenger cars in relevant categories, developed in The Netherlands in the 80's would have left the lightest of the three categories, under 850 kg, completely depopulated if the trend till 2000 would have continued. However, weight is also a measure for CO_2 emission. In a conservative estimate, 100 kg extra yields 7.5 gram CO_2 per km extra for the test value. As rule of thumb one could say that for urban driving the fraction additional weight translates directly into the same additional CO_2 emission. The NEDC test is carried out with a single driver and some fuel, but no additional weight.

On the motorway, i.e., at constant but high velocity, the weight plays a smaller role. However, recent findings indicate that for the rolling resistance as well the additional weight has an almost similar effect proportional to weight. For real-world emission, consequently the motorway part in driving, which is hardly represented in the NEDC, heavier cars have less deviation from the type-approval CO_2 emission. The notable exception to this rule are SUVs which have also a large frontal surface and limited aerodynamic streamlining. Consequently, they have large real-world CO_2 emissions compared to similar heavy vehicles. The type-approval test is performed with the lowest weight possible.

2.3 Driving behaviour and vehicle usage

Drivers are ultimately responsible for the largest variation in CO_2 emission per kilometre. About 30-40% variation can be found among drivers of the same make and model car. At all road types these variations occur. On the motorway, driving at 100 km/hr or 130 km/hr as a rule will yield such difference. Also the weight in the vehicle: three passengers with luggage in a small passenger car of 900 kg will, in particular on urban roads generate similar effects. Both effects can easily be deduced from physical models of vehicles, taking into account the additional inertia at acceleration and the air resistance at high velocities.

Coast down testing on common passenger cars yield a velocity-dependent force, varying between 160 N at 20 km/h, 280 N at 60 km/h, 500 N at 100 km/h, and 650 N at 120 km/h. Hence, based on force, the CO_2 emission would increase on average by 30% if one chooses to drive 120 km/h instead of 100 km/h on the same stretch of road. By the limitation of the engine power, which has to increases with the square of the speed, the dynamics at high velocity is typically lower.

However, although the variation of fuel consumption with individual drivers is well known, the actual source of this range is still unclear. Probably it is a combination of driver's vehicle usage, some by free choice, like the cruising velocity on the motorway, and some inherent to the particular ownership, like the number of passengers.

2.3.1 Influence of driving style

Some of the choices a driver makes are the driving styles. Ecodriving and proper gear shift strategies have effects estimated up to about 10%, however, the reference state, i.e., "the bad driving," is rather arbitrary. This is also a problem determining the national average driving style and vehicle usage. For example: how often is the air conditioning used in a country like The Netherlands is not well known.

Someone who never shifts beyond second gear in inner cities, or keeps speed despite approaching a red traffic light will have much higher specific fuel consumption. From our studies a 30%-40% power dissipation in the brakes of the total power consumption is considered normal urban driving. Hence a lot can be gained by proactive driving styles. On the motorway braking is hardly an issue, the possible gains are therefore smaller.

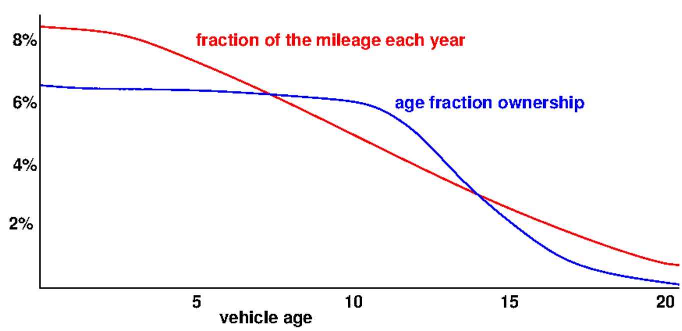

Figure 2 From the ownership the age distribution is more constant than from mileage. The mileage is linked to the distribution on the road types and typical usage. Fluctuations due to the economy are smoothed over.

2.3.2 Influence of milage and trip

Another important aspect of usage, besides driving style, auxiliaries and weight, is the mileage and trips. Modern vehicles spend more time on the motorway and in the early-morning rush hour than older vehicles. In particular in the Netherlands, the first three to four years vehicles are often in lease contracts, or other business-related use. Thereafter, private owners take over and the total mileage increases at a more leisurely pace. However, vehicles get better every year, the average scrapping age has increased to 17 years and younger vehicles have a higher mileage. A petrol car from 1987 has on average done 135 000 km in 2011 while for a car that is four years younger, the mileage is now already 160 000 km. For diesel vehicles this difference is even larger: in 2011 vehicles from 1987 had an average mileage of 245 000 km and for vehicles from 1991 this distance is 300 000 km. The second half of this lifetime is spent more casually, avoiding rush hours thereby decreasing the emission per mile, but increasing the urban share with the opposite effect. Consequently, diesel vehicles have more effect on the total emissions, and the effect of current vehicle sales will play a role, although shifting and decreasing, up to 20 years later. See Figure 2. Furthermore, population research in a city like Amsterdam shows that in such a metropolitan area, most trips are 5 km or less, so having a substantial portion of the CO_2 emission due to a cold, or luke-warm engine.

2.4 Congestion effects

Removing congestion is considered a good policy for several reasons, both economic and environmental. Indeed in urban situations with heavy congestion the pollutant emissions are typically twice the free flow emissions. The CO_2 emissions also increases, but not by factors. However, the nature of congestion is hard to define. Simple estimates of traffic light control predict large improvements but often ignore side streets and also often misses out on the shift of the congestion from the region under consideration to another region of the city. (2)

The complete picture of the total fuel consumption of a passenger car arise from combining the four corners. The linking pin the distance: total distance during its lifetime, distance on each type of road, distance in congestion, distance with heavy load or passengers, distance with air-conditioning on, etc.. (3)

3 FUEL CONSUMPTION AS THE LUMPED SUM

Traditionally, CO_2 emissions of transport are determined from the fuel sales. It will give a complete and accurate picture of the total emission. However, it does not provide any insight in the levers to reduce the emission effectively, other than reducing the overall mobility.

For the total CO_2 emission, i.e., the fuel consumption, combined with the distance travelled is good indicator. The fuel contains a more or less fixed fraction of 86% weight carbon atoms, which is almost completely converted to CO_2. (For gaseous fuels this fraction is slightly lower, with more energy per kilogram fuel.) TNO has carried out analyses of this type using data from the fuel-pass company Travelcard since 2008. For more than 300 000 vehicles the mileage and the fuel-sales were logged, in separate transactions.

Initially different brands of vehicles seemed to perform differently in the comparison between actual emissions and the type-approval test. However, plotting the actual fuel consumption as a function of the corresponding NEDC test result, showed a global trend, where the deviation between real-world CO_2 emission and test increases over time. The smaller deviation of some brands was due to larger and heavier vehicles models.

Apart from urban, low velocity driving, cold start is one of the aspects covered more extensively in the NEDC test than it occurs in the real world. It is not necessarily wrong to cover these aspects more: most technological gains, both for CO_2 and pollutants, can be made here. See Figure 3. Originally, there has been a substantial difference between the efficient diesel engine at low engine loads and the spark-ignition engines. Nowadays, petrol engines perform much better with low loads. This can been seen from the decreasing difference between the UDC and the EUDC test results. In the trend from 2004 to 2011, the higher [g/km] CO2 emission on the urban part, compared with the full NEDC, has decreases on average from 134% to 128% for petrol, and from 130% to 122% for diesel. In the same period the average NEDC value has decreased by 24% for petrol and 29% for diesel.

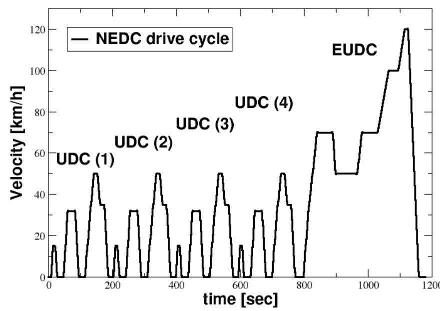

Figure 3 The type approval test, for factory values of CO_2 emissions.

3.1 Combining vehicle technology and driving behaviour

Not unduly impressed with the lower emission limits and test results, and from the indication of a limited effect on air quality of the improvements so far, the Dutch government has set up elaborate programme of monitoring. Part of this programme is the in-use testing of vehicles from private owners, on their performance under real driving conditions. At TNO tests are developed and vehicles are chosen to map the outcome directly to the real-world emissions used in the national air-quality models. The variation with road types, congestion, and vehicle technology are recovered by analysing the variation in the results, with the variation in tests parameters. This work resulted in the TNO emission model Versit+, an emission model to calculate vehicle emissions like NOx, NO_2, PM10, HC, CO and CO_2 for specific vehicle categories for specific traffic situations, in particular for a given speed and acceleration.

The Versit+ emission model, combined with information of the vehicle fleet composition, number of kilometres travelled by specific vehicle classes on specific road types under specific traffic conditions, driving behaviour, the use of airconditioning, deterioration effect etc. allows the modelling of real world vehicle emissions and fuel consumption. In this way effects of policy measures and technical developments can be quantified on vehicle category and vehicle park level.

In the Versit+ model as used by TNO the instantaneous CO_2 emission rate in g/s is modelled as a piecewise linear function of the instantaneous speed and acceleration only. This is a huge simplification of the situation. As can be read from the power law, the power demand depends among others on the mass and frontal area of the car, or the 'size' in more global terms. It seems logical that the automobile manufacturers design their cars such that the power of the engine is suitable for the power demand of a car of the size given. Hence, `size' (mass, area, volume) and `power' will be correlating quantities within the vehicle population. The power required for a given type approval driving pattern will translate into the type approval value. This type approval value in turn will then correlate with the `size' (mass, area, volume) and engine power. Therefore, though there are many physical parameters characterizing a vehicle, already the inclusion of one of these into the individual vehicle model is expected to give an improvement to the predicting power of the model. Including additional parameters will only give a limited extra improvement, because of the correlation with the others.

Recently, we have made a model where we included the type approval value of the CO_2 emission into the model as a linear prefactor and observed that this indeed improved the predicting power of the model on the subset of our dataset of test cycles that are not type approval cycles. We used the Akaike Information Criterion to quantify this. In another study, where we included mass, power and power to mass as extra parameters, we observed that including more than one of these three gave little additional predicting power, if any, (as quantified by a lower AIC) as compared to a model that included only mass as extra parameter, thus confirming the considerations in the beginning of this section (most physical car parameters are correlated, hence only one is sufficient for a substantial improvement of the model). In a model with the type-approval value included, including mass and/or power as extra parameters, often resulted in a higher AIC (i.e. a worse predicting power), to make the picture more complete.

This augmentation of the TNO Versit+ emission model allows one, next to vehicle technology, and driving cycles (intermediates of the combined road, driving behaviour, and congestion effects on emission), to include the type-approval value of the CO_2 emission for an improved real-world emission for that particular situation. Since these type-approval values are widely available, the typical trouble with determining the vehicle input parameters of the model is limited.

3.2 NEDC test result as ubiquitous measure for fuel consumption

The single most used and quoted number for fuel consumption and CO_2 emission is the result of a vehicle on the NEDC test. It is a single reference, and, as any test, will never account for all the variations in real world. It should be treated as a measure of the vehicle, for example, to be used in vehicle comparison. Its significance for effectiveness of policies is degrading. To use it for forecasting, a better understanding of the relation between type-approval value and actual fuel consumption is needed. The fuel-pass data provided by Travelcard makes it possible to make such a detailed comparison.

By modern standards of actual driving, the NEDC as sum of UDC and EUDC still has a focus on low velocities and many stops. The typical velocity on the European Motorways, i.e., 120 km/hr, is just about reached, but not maintained. In The Netherlands a 130 km/hr speed limit was recently introduced. The fact that this velocity is beyond the test range may raise concerns for the real-world emissions. For older vehicles, one can say that velocities and accelerations covered in the NEDC test generate a region in driving behaviour with flat, low emissions. Outside this region the real-world emission are not necessarily proportional, but increase with more strongly. In the last years, the NEDC test results and real-world emissions seem to decouple: real world emissions cannot be predicted from the NEDC value..

Another important change in the test is the cold-start as part of the test, introduced in 2000. At the start of a trip with a cold engine, especially spark-ignition engines (petrol, LPG, CNG) with three-way catalysts, and of trucks with SCR after-treatment, the catalyst will not function and initial emissions are substantial. To stimulate improvements of the start-up, a cold-start became part of the test. For passenger cars since 2000, for trucks the introduction will only be with Euro-VI and the WHTC test. Not only the pollutants, but also the fuel consumption suffers a little from a cold start, without an initial 40 seconds idling. As a rule of thumb about 100 gram CO2 can be assigned to the cold-engine effect of a passenger car, but its effect spreads out over the first 4 to 5 kilometres of driving.

3.2.1 Decomposing the NEDC: UDC and EUDC

The old driving cycle, the ECE test, became the first half of the NEDC test. In 1990 the Extra-Urban Driving Cycle (EUDC) was added to the Urban Driving Cycle (UDC). Before 1990 the fuel consumption was given for the UDC and two constant velocities of 90 and 120 km/hr. Some vehicles were optimized in fuel consumption for these velocities. However, as real world driving is different, these numbers were not necessarily a correct indication of the real world fuel consumption.

All in all, one would expect the NEDC CO_2 emission could even be somewhat higher than the real world emission. The UDC part is responsible for that, for two main reasons: the cold start and the low velocity and number of stops. For that reason the UDC test has been a force behind the technological development which is visible in the different between the UDC test value and the EUDC test value which has decreased significantly in the years 2000 to 2010. Most CO_2 reductions on the full cycle are made on the UDC part. In particular hybrid vehicles show very little difference between the two parts of the test. Hence, if modern vehicles uses were urban, the difference between real world en type-approval value would not be that large.

The usage is not the full effect. A low type-approval value, with its benefits, has become a sport, were the rules are open to some interpretation. The same testing of the type-approval, carried out by TNO yield substantial higher values, of up to 20%. Half of this difference is from the OEM determination of the rolling resistance, air resistance, and weight, in that order, compared to the laboratory coast down. The other half is from the chassis dynamometer test itself, i.e., optimal driving, minimized auxiliaries usage, and other flexibilities in the test procedure.

The reduction of the type-approval value seems in part driven by the pecuniary incentives, like road-tax differentiation. The record values obtained by the OEM's seem impossible to obtain by other parties. Many of the flexibilities in the testing procedure seem to be exploited. Although, every driver can monitor the fuel consumption, a unobtainable reference value from the OEM is not widely questioned. In part this acceptance might be due to the complexity, involving usage and drive styles.

3.2.2 NEDC focus on low engine load

Figure 4 shows the driving profiles of three different driving cycles. The NEDC cycle, the cycle used in the Type Approval test, the Common Artemis Driving Cycle and a Dutch heavy congestion cycle are plotted in Figure 4. The common Artemis driving cycle is developed in the European Artemis project and was designed to represent average European driving behaviour. The Dutch heavy congestion driving cycle was developed by TNO in order to represent the average Dutch driving style under severe congestion traffic. Every dot in the Figure 4 represents the velocity-acceleration combination of each single second of the specific driving profile.

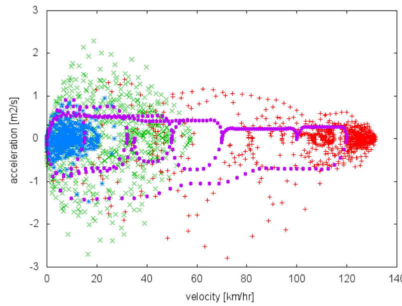

Figure 4 Different real-world driving cycles (red +: CADC motorway; green x: CADC urban; blue *: dutch heavy congestion) compared with the NEDC test (magenta bullets). The NEDC test has a limited variation, low accelerations, and specific constant velocities.

The magenta dots, which represent the NEDC Type approval cycle only cover a very limited set of accelerations and velocities. The highway conditions, as presented by the red dots of the CADC highway cycle, are hardly covered by the NEDC. The urban driving conditions as presented by the green dots of the CADC urban part are also hardly covered by the NEDC cycle.

The average velocity on the NEDC is 33.6 km/hr, over 11 km. This is the combined value of the UDC and the EUDC. The UDC part has many stops and idling. The maximal velocity is only carried for a short time. Hence the engine load, both from idling and low velocities, is low. Furthermore the maximal accelerations are about 1.0 m/s^2, which is substantially lower than the 2.0-2.5 m/s^2 accelerations in urban situations, and the 1.5-2.0 m/s^2 acceleration in extra-urban and motorway situations. Note: an acceleration with 1.0 m/s^2 would mean it takes 20 seconds and 200 meters to reach 72 km/hr from rest.

At high engine load the efficiency of the engine is limited by physical principles, such as the Otto and Diesel cycles. At low engine load, typical for the high-powered passenger cars of nowadays, this limitation has not been reached. Actually, with increasing engine power, and increasing congestion, without the NEDC test as indicator of overall performance, the fraction of actual load of rated power would have gone down with a worse real-world performance as its consequence.

From the rolling resistance and weight of a number of common vehicle models the amount of work needed in the NEDC can be assigned to different aspects. Rolling resistance work requires globally 60% of the work, 25% inertia, and 15% other loss factors, such as low-load reduced engine efficiency and idling.

3.3 Travelcard analysis

TNO has investigated fuel card data (4). We summarize the main findings here. Tank events corresponding to a large group of vehicles have been analysed. Thus real world fuel consumption per distance could be derived for every vehicle in the set. For these vehicles, type approval fuel consumption data according to the NEDC were also available. Thus, the ratio between real world and type approval value could be determined. It turned out that this ratio v can be expressed in terms of a quadratic function (with coefficients $\alpha_1, \alpha_2, \alpha_3$) of the type approval value n, plus additional terms (technology factor ϕ and usage factor η).

$$\upsilon = \alpha_0 + \alpha_1 n + \alpha_2 n^2 + \beta_1 \vartheta + \beta_2 \varphi .$$

The technology factor is related to the difference of the type approval values for city and outside-city and the usage factor is related to the average distance travelled by the vehicle per day. The usage factor is indirectly related to road-type: with 150 km per day, a vehicle will not likely stay within city limits. Both the technology factor and the usage factor have a limited effect of a few per cent. The results are dominated by the type-approval value.

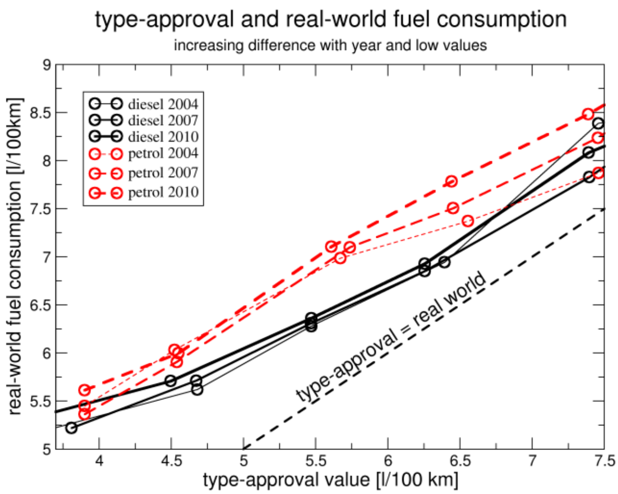

Figure 5 Real world versus type-approval fuel consumption

From Figure 5, we read that the real world fuel consumption is larger than the type approval value. This deviation is larger for more fuel-efficient cars. For petrol the deviation is larger than for diesel. However, the comparison of CO_2 emission puts the lines close together, as one litre petrol yields 2.38 kg CO_2 and diesel 2.66 kg. The difference between real-world and type-approval increases slightly with the years, however, the larger difference with the shift to lower type-approval values is dominant.

Apparently, in the real world situation, drivers have a driving pattern that deviates from the NEDC. The NEDC has a limited high velocity part. In practice, drivers drive a large part on motorways, where velocities are high and as a consequence, CO_2 emission and fuel consumption is large.

3.3.1 Increasing deviations as trend

As a follow-up of this investigation, we have analysed the relation between NEDC type approval and real-world CO_2 emission in the period 2004-2011. The fuel consumption did go down in this period, based on the data for 300 000 vehicles. See Figure 6. Average petrol fuel consumption has decreased by 13%, diesel by 5%.

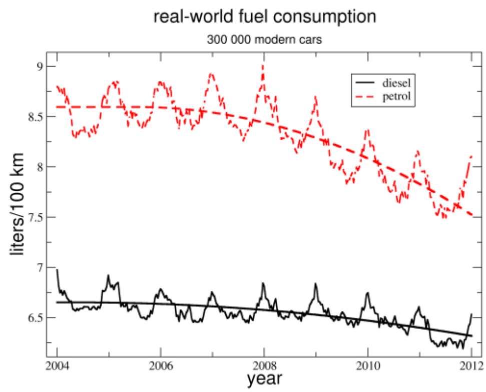

Figure 6 The global trend and seasonal fuel consumption

However, the type-approval values have gone down much more. Comparing, by introduction date on the Dutch road vehicles by type-approval value and average fuel consumption show an increasing deviation between the downwards trends.

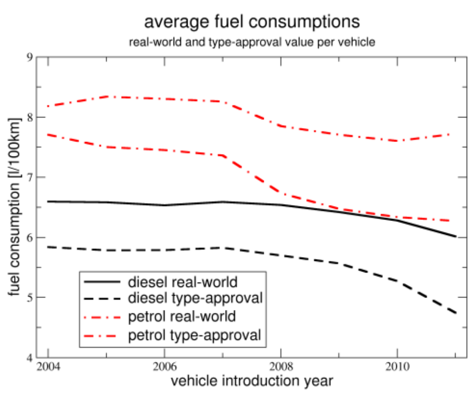

Figure 7 The change in average type-approval and real-world fuel consumption

From Figure 7, we conclude that for later years, the deviation between real world and type approval fuel consumption seems to grow, both for petrol and for diesel. There is a second trend, next to that from the functional behavior, that with in the vehicle population, fuel efficient cars become more prominent. Hence, within the population, vehicles with a large deviation between NEDC type approval fuel consumption and real world fuel consumption, become more numerous as the type approval value decreases.

6 CONCLUSIONS

In this paper many interlinked aspects of CO_2 emissions of, mainly passenger cars, are covered. Despite the many existing links, distinguishing the four major aspects of vehicle emissions are central to the emission models used. In some cases, data will yield only a projected view, e.g. the results of a total trip or lifetime, or measurements on a particular road type. Assigning effects back to a particular aspect requires some complex analyses. These details were not covered in this paper.

Separating the effects into four groups, the responsibilities are also separated: stimulated by Europe the OEM's introduce the new technologies. Different road-types fall under respective authorities, such as highway authorities, and the regional and municipal councils. The congestion can be reduced by planning authorities, routing tools and ITS measures. Finally, but not least, the individual driver, with its choices and driving behaviour is a major player in the real-world CO_2 emissions. The breakdown of the variation due to individual drivers is a difficult problem under continuing investigation.

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