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Investigations for an Amendment of the EU Directive 93/116/EC (Measurement of Fuel Consumption and CO_2 Emission)

Executive Summary

By order of the German Environmental Agency (UBA)

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1 Tasks and measurement programme

The measurement of fuel consumption and CO_2 emissions has become mandatory during the type approval procedure for M1 vehicles (cars) in the EU with the introduction of directive 93/116/EC. Within the context of the discussions about the global warming of the atmosphere the lowering of the CO_2 emissions and thus the lowering of the fuel consumption has become an important target for the vehicle industry. But the measurement method of the above mentioned directive is not suitable to consider influences of additional aggregates like air conditioning systems or the influence of new transmissions (6-speed gearboxes, advanced automatic gearboxes) allowing fuel consumption reducing gearshift strategies. Without these influences the CO_2 emissions of the car fleet cannot be calculated realistically enough.

In order to get quantitative information about the variances of CO_2 emissions and fuel consumption as well as the limited pollutants the following influences should be considered within the frame of this project:

- Different versions of a vehicle type
- Different gearshift strategies
- Air conditioning system (AC)

Another task was related to information about the use of air conditioning system in cars. This task was performed together with IFEU, Institut für Energie- und Umweltforschung Heidelberg GmbH. IFEU developed a questionnaire about the use of the AC. This questionnaire was presented to customers at several stations of TUEV Nord, where inspections at regular intervals were performed. The questionnaires were then sent to IFEU for further analysis.

The influences of vehicle version and gearshift strategy can be measured on ordinary test benches. But the influence of an air conditioning system requires a special test bench with solar radiation equipment if the worst case shall be included. Since TUEV Nord does not have such a test bench, it was originally planned that vehicle manufacturers would allow TUEV Nord to use their test benches for the measurements and that they support the project by additional funding in order to increase the number of test vehicles.

Unfortunately the vehicle industry refused to co-operate so that only four cars could be measured during this project. All of them were equipped with an air conditioning system. Two of them (No. 3 and 4) were measured with the air conditioning systems working on a test bench with solar radiation at the Delphi facilities in Luxembourg.

The following driving cycles were included in the test bench measurements:

- The European type approval test cycle (NEDC), consisting of four urban cycles and an additional extra urban cycle
- The US type approval test cycle (US FTP 75)
- The Common Artemis driving cycle (CADC), consisting of an urban, a rural and a motorway part.

The vehicles were tested in different vehicle modifications (tyres, mass, spoiler etc.), different gearshift strategies (as foreseen in the directive and with gearshifts at lower/higher engine speeds), two different start temperatures and with and without AC operation and in one case in some additional conditions.

The above mentioned variants were not fully applied to each vehicle and cycle.

2 Results of the test bench measurements

2.1 Bag results

The bag results for the pollutants CO, HC, NOx, the CO_2 emissions and the fuel consumption were measured/calculated and analysed. The CO_2 emissions include the HC- and CO-contributions. The fuel consumption is calculated from the CO_2 emission as foreseen in 93/116/EC. The major part of the measurements was carried out two times. The test bench settings were adjusted to the results of coast down measurements on a test track.

With one exception the measurement results for the base case (type approval variant) and the other variants for HC and NOx are far below the EURO IV limit values for the NEDC. Even the results for the other variants do not reach the limit values for both pollutants, if the AC is switched off. The situation is a bit different for CO. The base case result is below the limit value, but for engine speed optimised gearshifts the CO emission exceeds the limit value and also the HC emissions are significantly higher, although this operation results in a CO_2 emission reduction.

There is a general tendency for the NEDC that HC and CO emissions decrease with increasing CO_2 emissions while NOx follows the CO_2 trend. And it must also be mentioned that the emissions of HC and NOx tend to zero for extra urban driving conditions. This is also the case for CO, but only for the NEDC.

Due to the higher speed range and dynamics the CADC cycle results show generally higher emission levels and variances between the variants than the other two cycles. The HC and NOx emissions are still low compared to the EURO IV limit values. But the CO emissions are high, even in hot conditions. If the AC operation variant is disregarded, the two extremes are formed by the two extreme gearshift prescriptions: optimised gearshifts leading to the lowest CO_2 emission and gearshifts at 4000 min^{-1} leading to the highest CO_2 emission.

The total gearshift related differences for the CO_2 emission are about 25% for urban and rural operation. For motorway operation the gearshift related differences are below 2%, which can be expected because motorway operation is predominantly carried out in the highest gear.

On the other hand, the vehicle related differences (worst case versus best case) increase with increasing speed. For urban operation the CO_2 emission difference is lowest and highest for motorway operation. This tendency can also be found in the NEDC results.

One of the vehicles was equipped with a Diesel engine. For this vehicle the CO and HC emissions are close to zero for all cycles. On the other hand, the reduction strategy for NOx seems to be optimised for the type approval test cycle.

The smallest vehicle was equipped with a simple air conditioning system that was controlled by on and off operation. The NEDC was driven with and without AC operation at the TUEV Nord test bench with a start temperature of 23 °C and the AC set to full cooling capacity. Already this operation led to significant differences in the emissions. With AC the CO_2 emissions were 37,4% higher.

The CO emission was increased by 141%, the NOx emissions were 10,9 times higher than without AC.

The differences with and without AC were much more drastic for the tests with solar radiation. In this case the room temperature was set to 35 °C and the solar radiation was 850 W/m². This operation led to extremely high emissions (+53% for CO_2, 9,5 times higher value for HC, 63 times higher value for NOx and 193 times higher value for CO). The NOx emission with solar radiation and a starting temperature of 35 °C was 0,45 g/km instead of 0,08 g/km, the CO emission 9,9 g/km instead of 0,12 g/km. This leads to the conclusion that the catalytic converter was totally out of operation during this test.

In several cases the NOx values for the CADC were significantly higher than for the NEDC and sometimes far above the limit values for EURO IV. The CADC was created within the 5^{th} framework project "Artemis" and was used for the development of emission factors for modelling purposes.

2.2 Analysis of modal data

2.2.1 General

For the major part of the measurements second by second emission data was also measured and analysed. This data gives some explanations for unexpected results related to the pollutant emissions. The analysis showed for example that in some cases the CO and HC emission is just a cold start problem, because the emission tends to zero after the second UDC (Urban Driving Cycle).

The analysis of the modal data was focussed on two main issues:

- Cold start influence
- Influence of air conditioning systems

2.2.2 Cold start influence

In order to assess the cold start influence the emissions were summarised for each cycle part separately. For the NEDC the emissions of the first two UDCs and the last two UDCs were added. The cold start contribution could then be calculated by the differences between both values. A similar approach could be used for the US FTP cycle by comparing the emissions of the first and the third cycle phase. The results were averaged over the different variants, because no significant variant influence could be found.

The cold start contributions varied between 64% and 98% for HC and CO.

For NOx the situation is different. There is only a slight effect of the cold start contribution on the total emissions for the Diesel vehicle, but a significant effect for the petrol vehicles (varying between 29% and 96%. The cold start increases the CO_2 emissions by between 9% and 22%.

2.2.3 Influence of air conditioning systems

The significant influence of air conditioning systems was already discussed in chapter 2.1 for each single vehicle. In this chapter the results shall be analysed more detailed. For that reason the second by second CO_2 emissions with and without AC operating are plotted versus vehicle speed for the NEDC and the CADC. "With AC" means tests at the TUEV Nord test bench with a room temperature of 23 °C, "with AC and solar radiation" means tests at the Delphi test bench with solar radiation of 850 W/m² and a room temperature of 35 °C.

The regression curves of the second by second data plotted versus vehicle speed show that the AC causes higher CO_2 emissions over the whole speed range. In addition there are distinctly different results between the vehicles and driving cycles on the TUEV Nord test bench with a room temperature of 23 °C and the Delphi test bench with solar radiation of 850 W/m² and a room temperature of 35 °C. The differences between both situations can be explained by the different start temperatures and cool down conditions. The results support the hypothesis that the extra emission of CO_2 in g/h is roughly constant over the vehicle speed.

The lowest influence on the emissions was found for vehicle 1, the highest for vehicle 3. One could assume that the influence on the emissions decreases with increasing rated power of the vehicle, but the vehicle sample is too small and inhomogeneous to support this hypothesis.

With respect to the pollutant emissions it should be mentioned first that there was an increase of the HC emissions in the major part of the results but on such low level, that this is no issue of concern.

Vehicle 3 showed already a high influence of the AC on the emissions for a temperature of 23 °C and no solar radiation. At a temperature of 35 °C and with solar radiation the additional load on the engine was that high that catalytic converter light off occurred, resulting in a tremendous increase of all pollutant emissions. It should be proven in the future whether this behaviour is typical for small cars and non automatic systems or if the vehicle was just an outlier.

For the other vehicles there is no uniform trend for the influence of the AC on the CO emissions, but at 35 °C and with solar radiation the CO emissions can be tremendously increased (up to a factor of 20).

The NOx emissions show a general trend to higher values with AC operation, but the increase depends very much on the individual vehicle. With solar radiation and a start temperature of 35 °C the increase in NOx emissions can amount up to 280%.

3 Questionnaires about the use of air conditioning systems in cars

Between summer 2003 and spring 2004 a questioning was accomplished by TUEV Nord during the vehicle general inspection, in order to be able to estimate the utilisation of air conditioning systems in passenger cars. Basis of the questioning was a questionnaire, which was developed by IFEU and co-ordinated with the Federal Environmental Agency and TUEV Nord. It contained questions to the clients of TUEV Nords annual inspection stations related to the vehicle (manufacturer, type, key number, drive system, capacity, registration year, mileage), to the air conditioning system (type and manufacturer of the air conditioning system) as well as questions to the customers about the use of the air conditioning system.

Altogether 388 questionnaires were filled out and evaluated. Due to this number and to the circumstance that only tester and customers of the RWTUEV/TUEV Nord were asked, the results can not clearly be regarded as representative for the use behaviour in Germany. Since it concerns qualitative statements however predominantly, the evaluation gives a good reference point for the user behaviour, particularly since no investigations were available for us, which determined the air conditioning system use more comprehensively.

The questions were predominantly completely answered, so that nearly all inquired information could be evaluated.

Type of AC system

In the questionnaire the type of A/C-system was asked. Altogether 227 vehicles were equipped with a manual and 159 vehicles with an automatic A/C-system. Manual systems were most frequently found in smaller petrol vehicles. Differentiated with respect to the year of construction a trend to automatic systems is recognisable for newer vehicles: Their share rose from 30% in the year 1997 to 60% in the year 2002.

If the different use frequencies are proportionally weighted and interpreted as time shares ("always" = 100%,"never"= 0%, the other options evenly distributed), this results in the following average use frequency for different situations:

- Automatic systems are usually switched on (frequency: over 80%, except in the winter with scarcely 70%)
- Manual systems are switched on clearly more rarely (frequency between 47 and 78%; winter: 33%)

4 Conclusions and recommendations for emission inventory modelling

The results of this study clearly demonstrated that there are significant influences on the CO_2 emissions and the fuel consumption related to vehicle and gearshift variants in the order of 10% to 15%. Since it can be assumed that the vehicle manufacturer uses an optimised vehicle for the type approval procedure the CO_2 emissions of the same type in real traffic is higher. In addition to that a comparison of the results for the NEDC and CADC leads to the conclusion that the CO_2 emissions in real traffic are systematically higher than indicated by the type approval results. To be on the safe side one can assume that the CO_2 emissions in real traffic are 15% to 20% higher than for the type approval cycle.

An optimised gearshift strategy (gearshifts at low engine speeds) results in a reduction of the CO_2 emissions in the order of 10%, but may lead to an increase of CO and NOx emissions. It should be discussed with vehicle manufacturers whether this increase can be avoided by further optimisations of the emission reduction systems. Anyway, campaigns like ECO driving should be supported as good measures for CO_2 reduction.

The results of the measurements performed with air conditioning systems in operation show quite clearly that their contribution to CO_2 emissions cannot be disregarded for emission inventories. If one considers in addition the results from EMPA (see [1]), where measurements were carried out at a series of different room temperatures one has to take into account the fact that the air conditioning systems even consume power and thus increase the CO_2 emissions, if the temperature is below the target temperature (20 °C to 23 °C), because the AC is used to dry the air of the vehicle compartment.

For modelling purposes the following approach is proposed. From the existing results estimates should be derive about the additional CO_2 emission in g/h caused by the air conditioning system as function of the temperature with and without solar radiation. These functions can then be combined with the statistical information from the questionnaire and additional information about the annual variations of the temperature and sunny/cloudy days in a specific region in order to estimate the air conditioning contribution to the CO_2 emission for emission inventories.

But more measurement results are necessary in order to bring the uncertainty of such a calculation down to a reasonable level.

5 Proposals for an amendment of the EU Directive 93/116/EC

5.1 Measurements of best case and worst case

The results of this research project have clearly shown that the CO_2 emissions for the NEDC test cycle can vary up to 30% for a specific vehicle type, due to vehicle and driving behaviour variations. Vehicle variations are related to differences in tyres, kerb mass, battery capacity etc., driving behaviour variations are related to different gearshift strategies. The vehicle variations influence increases the driving behaviour variations influence decrease with increasing speed. It is very likely that the CO_2 emission obtained by the current EU Directive 93/116/EC for a vehicle type is at the lower end of the variation range.

Such a result cannot be used as a representative value for the whole range of different variants of a vehicle type. In order to get information about the variation range for the CO_2 emissions it is proposed to amend the regulation in that way that the best and the worst case of a vehicle type family has to be measured and the influence of an air conditioning system has to be considered.

Furthermore in order to improve the precision of the measurement tolerances for influencing parameters should be reduced.

In particular the following requirements are proposed:

- The test bench settings shall be adjusted on the basis of on road cost down measurements, individually applied to the best and the worst case vehicles.

- For both variants (best and worst case vehicle) only OEM tyres with an inflation pressure as recommended by the manufacturer shall be used. The settings for chassis and brakes shall comply with the normal settings of these variants.

- The capacity of the electric battery shall be between 80% and 90% of maximum capacity for both variants in order to be better in line with practical use.

- The worst case shall include all power consumptive auxiliaries (except air conditioning systems) such as power steering compressor, suspension compressor, air compressor, seat heating etc.

- The gearshift prescriptions for manual transmissions shall be brought more in line with practical use as proposed in Annex A. Corresponding gearshift prescriptions, based on the same approach as described in Annex A, are used, accepted and validated for the ECE global technical regulation for the exhaust emission measurements for motorcycles (WMTC, see [7]). The gearshift prescriptions in Annex A represent two different driving behaviours: “average” and “high revs”. The best case measurements shall be carried out using the gearshift prescriptions for “average” driving behaviour, the worst case measurements shall be carried out using the gearshift prescriptions for “high revs”. For automatic transmissions the manufacturers recommendations shall be used for the best case, the most “sporty” mode shall be used for the worst case. Adaptive transmissions need to be conditioned accordingly before the measurements.

It may be discussed whether the measurement of the best case could be skipped in order to keep the measurement effort low.

5.2 Air conditioning systems

Air conditioning systems shall be covered by a third test. There is no need to include a cold start in this test, because the investigations reported in [1] did not show significant differences in the emissions with and without air conditioning systems during the cold start phase. The following parameters are proposed for the test with air conditioning system:

- Hot start condition
- Vehicle, test bench settings and gearshift prescriptions as for the best case, because only the influence of the air conditioning system shall be measured. If only the worst case has to be measured, this case has also to be used for the measurements with the air conditioning system working
- Air temperature 35 °C
- Relative humidity between 40% and 50%
- Solar radiation of 850 W/m², directed to the front screen of the vehicle
- Vehicle cooling air flow proportional to vehicle speed
- The AC settings shall be as follows:
  - Manual AC:
    - Highest mode (coldest)
    - Lowest temperature
    - Fan speed max.
    - Recirculation
  - Automatic AC:
    - Automatic mode
    - Target temperature 72 °F (22 °C)

- Other settings like manual, if applicable

The solar radiation is necessary in order to take into account the positive effect of specialized glass that transmits less heat from the sun to the interior of the vehicle. The radiation shall be activated three hours before the measurements in order to heat the interior of the vehicle. This requires that the windows are closed.

5.3 Conclusion

The results for best case (if to be measured) and worst case as well as for the extra emissions of the air conditioning system shall be made mandatory for declaration and shall be available as information for customers.

5.4 More realistic driving cycle

On a long term perspective the current type approval cycle (NEDC) shall be replaced by a more realistic cycle based on real world driving behaviour data analysis, as already done for motorcycles.

6 Literature

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[5] **Öko-Recherche 2001** Schwarz, W., Öko-Recherche: Emissionen des Kältemittels R134a aus mobilen Klimaanlagen; im Auftrag des Umweltbundesamtes; Frankfurt a.M., September 2001

[6] **Final Technical Report on Air Conditioning for the Federal Test Procedure Revisions**, Notice of Proposed Rulemaking, U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Mobile Sources, January 1995

[7] **H. Steven**, Worldwide Harmonised Motorcycle Emissions Certification Procedure, Technical report for the ECE-GRPE, Document TRANS/WP.29/GRPE/2004/10, March 2004

[8] **ROTRANOMO**, Development of a Microscopic Road Traffic Noise Model for the Assessment of Noise Reduction Measures, DELIVERABLE 42 - INTERMEDIATE REPORT ON THE POWERTRAIN MODEL, June 2004

7 Annex A - Proposal for realistic gearshift prescriptions

The existing gearshift prescriptions are vehicle speed based. This is not in line with practical use. For cars, light duty vehicles and motorcycles the driver normally shifts gears during acceleration phases at a fixed engine speed. This shift speed (normalised to the span between idling speed and rated speed) is a function of the power to mass ratio of the vehicle. Based on analyses of in-use driving behaviour data, carried out within previous projects (see [7] and [8]), upshift speed curves as functions of power to mass ratio were derived as shown in Figure 1.

For average driving behaviour and acceleration phases manual transmissions shall be shifted from 1. to 2. gear when the engine speed reaches a value according to the following formula:

$$n\_\max\_acc(1) = (1.7444 \times pmr^{-0.3159} - 0.1) \times (s - n_{idle}) + n_{idle}$$

equation 7-1

where pmr is the rated power in kW multiplied by 1000 and divided by the vehicle mass in kg
n_{idle} – idling speed in min^{-1}
s - rated engine speed in min^{-1} at max. power

Upshifts for higher gears and average driving behaviour have to be carried out during acceleration phases when the engine speed reaches a value according to the following formula:

$$n\_\max\_acc(i) = (1.7444 \times pmr^{-0.3159}) \times (s - n_{idle}) + n_{idle}$$

equation 7-2

where pmr is the rated power in kW multiplied by 1000 and divided by the vehicle mass in kg
n_{idle} is idling speed in min^{-1}
s is rated engine speed in min^{-1} at max. power
i is the gear number (≥ 2)

The minimum engine speeds for acceleration phases in gear 2 or higher gears are accordingly defined by the following formula:

$$n\_\min\_acc(i) = n\_\max\_acc(i-1) \times \frac{r(i)}{r(i-1)}$$

equation 7-3

where *r(i)* – ratio of gear i

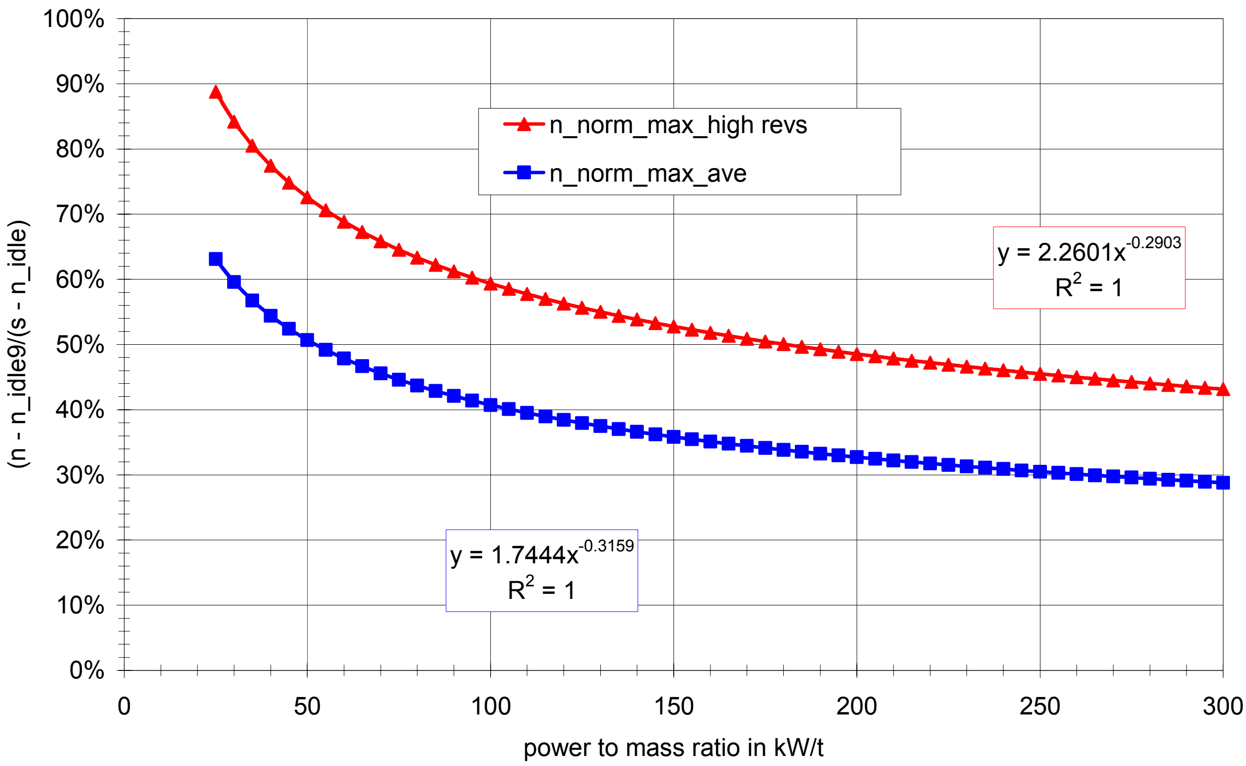

Figure 1: Normalised upshift speeds for cars (and light duty vehicles) in gears higher than first gear for average and high revs driving behaviour

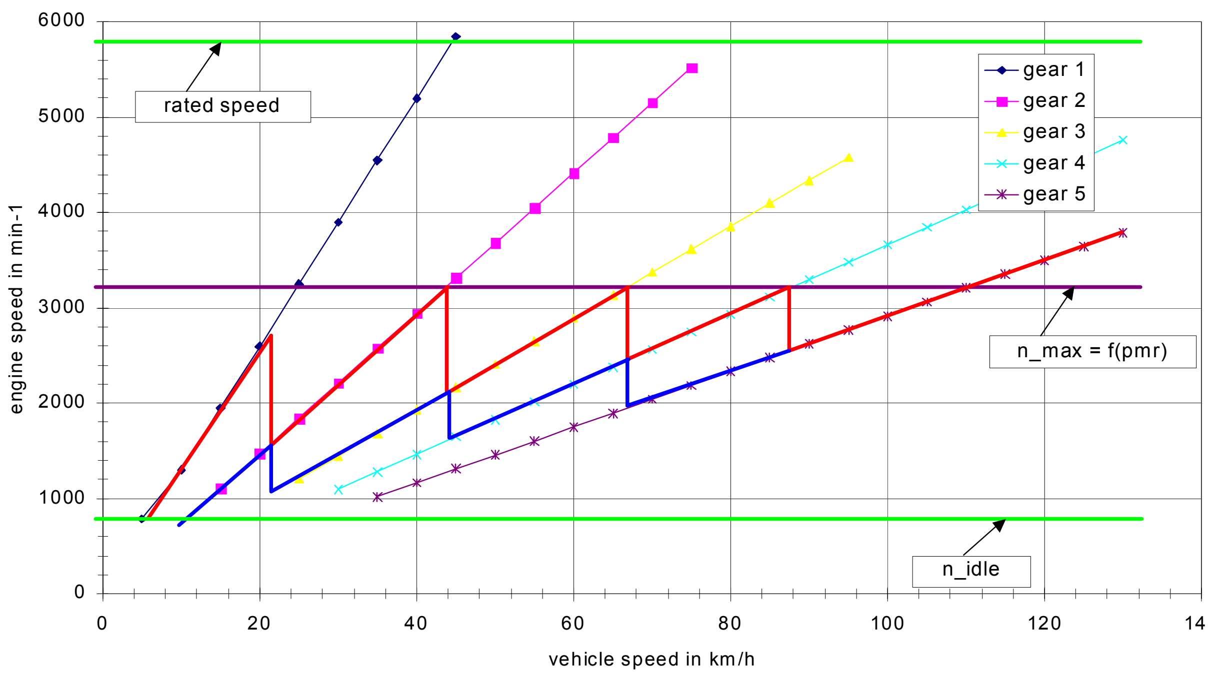

Figure 2: Example for a gearshift schema for a compact car. Upshifts and gear use during acceleration phases are coloured in red, downshifts and the additional gear use during constant speed or deceleration phases are coloured in blue.

The minimum engine speeds for deceleration phases or cruising phases in gear 2 or higher gears are defined by the following formula:

$$n\_\min\_dec(i) = n\_\min\_acc(i-1) \times \frac{r(i)}{r(i-1)}$$

equation 7-4

where *r(i)* – ratio of gear i

When reaching these values during deceleration phases the manual transmission has to be shifted to the next lower gear.

Figure 2 shows an example for a gearshift sketch. The solid lines demonstrate the gear use for acceleration phases; the dotted lines show the downshift points for deceleration phases. During cruising phases the whole speed range between downshift speed and upshift speed may be used.

Additional requirements

In order to avoid driveability problems these prescriptions have to be supplemented by the following **additional requirements**:

- No gearshift if a deceleration phase follows immediately after an acceleration phase.
- Downshifts to the 1. gear are prohibited for those modes, which require the vehicle to decelerate to zero.
- The 1. gear should only be used when starting from standstill.
- For those modes that require the vehicle to decelerate to zero, the engine speed is idling speed when the vehicle speed drops below 10 km/h or when the engine speed drops below $n_{idle} + 0.03 \times (s - n_{idle})$.
- The minimum time span for a gear sequence is 2 seconds.

Gear use calculation

Following the above prescriptions the gear use calculation is carried out in 3 steps:

Step 1: Calculation of shift speeds

Calculate upshift and downshift speeds for all gears according to the following formulas:

Upshift speeds in km/h during acceleration phases:

$$v_{1\to 2} = (n\_\max\_acc(1) \times (s - n_{idle}) + n_{idle}) \times \frac{1}{ndv_1}$$

equation 7-5

$$v_{i \to i+1} = (n\_\max\_acc(i) \times (s - n_{idle}) + n_{idle}) \times \frac{1}{ndv_i}$$ **, *i* = 2 to *ng*-1**

equation 7-6

Where *i* is the gear number (≥ 2)

ng is the total number of forward gears

n_{idle} is the idling speed in min^{-1}

s is the rated engine speed in min^{-1}

ndv_i is the ratio between engine speed in min^{-1} and vehicle speed in km/h in gear i

Downshift speeds in km/h during cruise or deceleration phases in gears 3 (3rd gear) to *ng* are calculated, using the following equation:

$$v_{i \to i-1} = (n\_\max\_acc(i) \times (s - n_{idle}) + n_{idle}) \times \frac{1}{ndv_{i-2}}$$, i = 3 to ng

equation 7-7

Where *i* is the gear number (≥ 2)

ng is the total number of forward gears

n_{idle} is the idling speed in min^{-1}

s is the rated engine speed in min^{-1}

ndv_{i-2} is the ratio between engine speed in min^{-1} and vehicle speed in km/h in gear i-

Step 2 – Gear choice for each cycle sample

Engine speed = idling speed

The engine speed is set to idling speed and the gear to 0, if the following conditions are met:

- During stop phases
- During cruise or deceleration phases in second gear, if
  - the vehicle speed drops below 10 km/h or
  - the engine speed drops below $n_{idle} + 0.03 \times (s - n_{idle})$

Gear choice for acceleration phases

Gear = 6, if $v > v_{5 \to 6}$

Gear = 5, if $v > v_{4 \to 5}$

Gear = 4, if $v > v_{3 \to 4}$

Gear = 3, if $v > v_{2 \to 3}$

Gear = 2, if $v > v_{1 \to 2}$

Gear = 1, if $v \leq v_{1 \to 2}$

Gear choice for deceleration or cruise phases

Gear = 6, if $v > v_{4 \to 5}$

Gear = 5, if $v > v_{3 \to 4}$

Gear = 4, if $v > v_{2 \to 3}$

Gear = 3, if $v > v_{1 \to 2}$

Gear = 2, if $v \leq v_{1 \to 2}$

Step 3 – Corrections according to additional requirements

The gear choice is then modified according to the following requirements:

1. No 1. gear during deceleration phases.
2. No gearshift at a transitions from an acceleration phase to a deceleration phase: keep the gear that was used for the last second of the acceleration phase also for the following deceleration phase unless the speed drops below a downshift speed.
3. No upshifts during deceleration phases.
4. No gearshift in cruising phases.
5. If an acceleration phase is followed by a deceleration phase and gear is first gear, keep first gear.
6. If a gear is used for only one second, this gear shall also be assigned to the following second in case of acceleration or cruising phases and to the preceding second in case of deceleration phases. Since it could happen that the modifications according to this criterion create new phases where a gear is used for only one second, this modification step has to be applied several times.

Corresponding gearshift prescriptions are used, accepted and validated for the ECE global technical regulation for the exhaust emission measurements for motorcycles (WMTC, see [7]).

The gear use calculation for high revs driving behaviour is calculated accordingly but using the coefficients of the approximation function for this driving behaviour as shown in Figure 1.