Cold Start Emissions of Passenger Car Fleets: a Simplified Physical Modelling Approach

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Abstract

The emissions during hot driving conditions, in which the exhaust-after-treatment systems are working properly, continue to decrease, which is why the emissions of cold starts have gained in importance. Traffic emission models are used to estimate and predict vehicle fleet emissions and the air quality of countries, regions, cities, etc. In addition to the statistical input of fleet activities, these models are mostly based on the use of separate emission sub-models for hot driving and cold starts. In reality, the cold start models are almost entirely empirical and of limited accuracy. In this work, a model is developed that is based on physical reasoning, i.e. it is based on energy balances. Because many details, such as the thermal conductivities and the engine control decisions are unknown, the model must be able to address different simplifications. The model can be parameterized with as few as two tests per vehicle. It is applied to several car samples (six to eight vehicles each) of different technical generations and shows reliable prediction for any combination of driving pattern, ambient temperature, stop time before the ride and duration of the ride (if shorter than the warm-up phase).

Introduction

Vehicle cold start emissions have become an increasingly important concern recently because the emissions produced by modern vehicles during hot running conditions are comparatively small and still decreasing (Weilenmann et al., 2009, Favez et al., 2009, Cook et al., 2007). In one cold start, the average Euro-4 gasoline vehicle emits as much hydrocarbons as during 300 – 2500 km of hot driving (Weilenmann et al., 2009). The reduced air quality of urban areas is often dominated by these cold start emissions that also contribute to secondary aerosols (Bahreini et al., 2012).

Traffic emission models are often based on separate sub-models for the hot running conditions versus the cold starts (Keller et al., 2009, Gkatzoflias et al., 2012, Joumard et al., 2007). The user combines the output of these models with the particular statistical data for the region in mind, e.g., the road characteristics, the traffic density distributions, the fleet composition, the ambient conditions, the trip distance distributions, etc. While the sub-models for hot running conditions exhibit a high level of complexity, the cold start sub-models are often comparatively simplistic, even though the list of parameters that influences the cold start emissions is longer than that for hot driving; specifically, ambient temperature, the stop time before the ride and the driving distance (if shorter than the warm-up) play a role, in addition to the driving pattern, which is also needed to describe the hot emissions. These cold start models mainly interpolate the available measurement data and thus are purely empirical. These models show the following drawbacks: As they are based on data from only one cold driving pattern, they are not applicable to different driving situations. As measurements on chassis dynamometers show certain repeatability errors, certain inconsistencies occur (e.g. higher cold start emissions at -7 than at -20 °C). The sub model for reduced stop time is uncertain.

The new model presented here was developed to overcome these drawbacks. The warm-up phase of an engine and its after-treatment system are mainly driven by energy balances. Thus, this model is based on the amount of heat energy available to warm up the components.

A first sub-model estimates the energy fed to the engine by the fuel as a function of crankshaft power delivered in hot running conditions. A second sub model estimates the additional fuel energy needed in cold start to overcome increased friction. The next sub-model estimates pollutant emissions in a first phase of warm-up, where the catalyst is inactive as temperatures are too low for conversion. A next sub-model describes the pollutant emissions in the second phase of warm up, where parts of the catalyst are sufficiently warm to convert pollutants. Finally, a cool down model for engine and catalyst temperatures is developed for the situation of short time parking.

Boundary conditions

As this model should be parametrisable with data from emission inventories, only a limited set of data is available from each car and test: vehicle mass, driving resistance, engine capacity, gear box ratios, and as time-coded signals: velocity, CO_2 and pollutant emissions. However, neither data on thermal conduction of engine or catalyst mass, insulation coefficients, etc. nor pre catalyst emission signals are available. Thus the model needs to deal with a number of simplifications.

Engine control has many possibilities to influence both fuel consumption and emissions during the warm-up of a vehicle (e.g. air fuel ratio, ignition/injection time), that can be manipulated on various criteria; such as different temperatures, running time, engine load, etc. As all these strategies are unknown, the physics based model will need certain empirical adjustments. As this model clearly simplifies many details, it shows some uncertainties. However, these uncertainties are clearly smaller than measurement repeatability and they are free of bias when fleet values are generated by averaging different vehicle data.

Data of 31 cars and 115 cold-start tests was used for model development and validation. Pre-catalyst emissions and temperature signals were partly available from tests.

Engine model

The engine model splits up into a sub-model for hot running conditions and a cold start model. For hot running conditions the chemical power delivered by the fuel may be modelled by engine maps or a Willans approach (Pachernegg, 1969, Rizzoni et al., 1999) if crankshaft power and speed are known. These latter values result from the vehicles velocity and acceleration in the given driving pattern. In contrast to engine theory, certain corrections need to be applied for motoring, idling and starting (clutch or converter losses) in complete vehicle simulation (Weilenmann et al., 2012). Using the Willans approach four parameters are sufficient to describe the model. These parameters are estimated automatically from test signals (as will all parameters of the following sub-models). Figure 1 shows the prediction quality in a transient cycle.

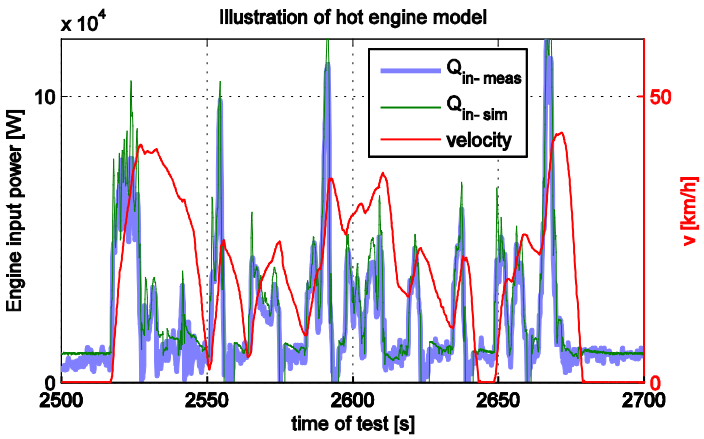

Figure 1: An illustration of the quality of the hot engine model. Blue: measured energy flow to the engine. Green: simulated energy flow to the engine. Red: vehicle velocity. Data from a gasoline Euro-3 vehicle using IUFC15-test cycle (Andre, 2004): This cycle repeats the shown velocity pattern of an urban ride 15 times to cover the whole warm up phase and features repetitions (> 5) in hot running conditions for averaging.

Extra fuel power in cold start is modelled as a function of engine friction that decreases with rising temperature. For modelling the rise of the engine temperature the energy balance is applied: The chemical power delivered by the fuel goes into mechanical work and heat. Part of that heat flows to the exhaust system, while the rest heats up the engine. Heat losses are assumed to be negligible as the coolant circuit is closed in this phase. The engine cold start model that predicts extra fuel power during cold start needs only two parameters to show a quality as in Figure 2 (Weilenmann et al., 2012).

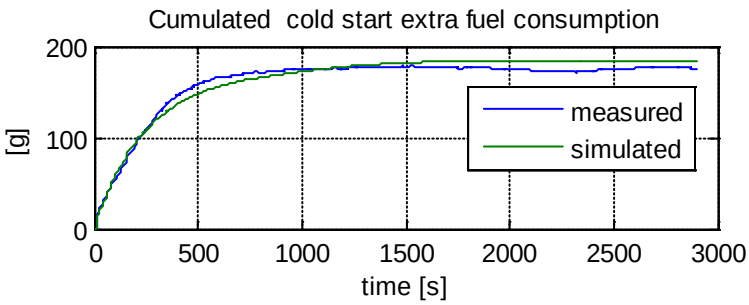

Figure 2: An illustration of the quality of the cold start engine model for a test at -7 °C (Test cycle as in Figure 1). Blue: measured cold start extra fuel consumption. Green: estimated cold start extra fuel consumption.

It has to be noted that measurement errors may distort this picture significantly: The chemical input power and fuel consumption is nearly proportional to (measured) CO_2 emissions. The CSEE (cold start extra emissions) of CO_2 that are determined as a difference of the emissions of cold and hot driving (in the same cycle) show a repeatability error of ± 48%. Thus the end value of the blue curve in Figure 2 may be 48% lower or higher than shown. As the model is parameterised using at least three tests per vehicle, these measurement errors are levelled out while parameterising one car and even more when averaging over a sample of cars.

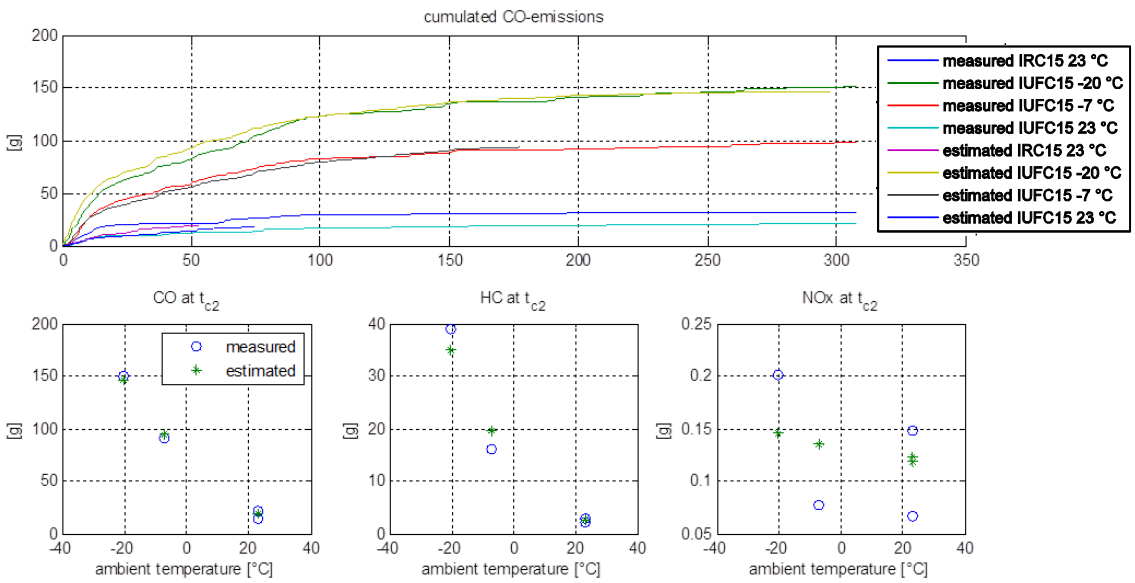

Figure 3: Illustration of prediction quality of the pollutants models for period one. Top: emission signals over time for CO of four different cold start tests of one car. Bottom row: comparison of the end values of all pollutants of the same tests (cycle description see legend of Figure 5).

Emissions model

The models for CO, HC and NO_x are very similar to each other and show two periods over time (Weilenmann et al., 2012). The first period is characterized by a non-stoichiometric air fuel ratio and catalyst temperatures below light-off. Emission concentrations are determined by the combustion process of the engine. The quality of this combustion process is assumed to depend on the temperature of the cylinder walls. Thus, after engine start emissions show a first maximum that depends on initial engine temperature and further on decrease roughly continuously when the cylinder walls heat up. Figure 3 shows the model quality for one car for the prediction of pollutant CSEE. For CO the model shows to be very accurate. The discrepancies between measurement and prediction for HC and even more for NO_x originate again from the larger repeatability errors of the individual measurement (up to ±40%) rather than from modelling errors. They level out for measurements over groups of cars.

In the second period of warm up part of the catalyst is above light-off and thus low amounts of pollutants may be converted, while at high mass flows (high loads) conversion drops. As the part of the catalyst that can convert pollutants is growing during that period, the threshold of mass flow below which conversion is good, rises. Figure 4 gives an example where emissions are elevated as long as the actual exhaust gas mass flow is above that threshold. The threshold is modelled to rise with the amount of energy delivered to the catalyst by the exhaust gas.

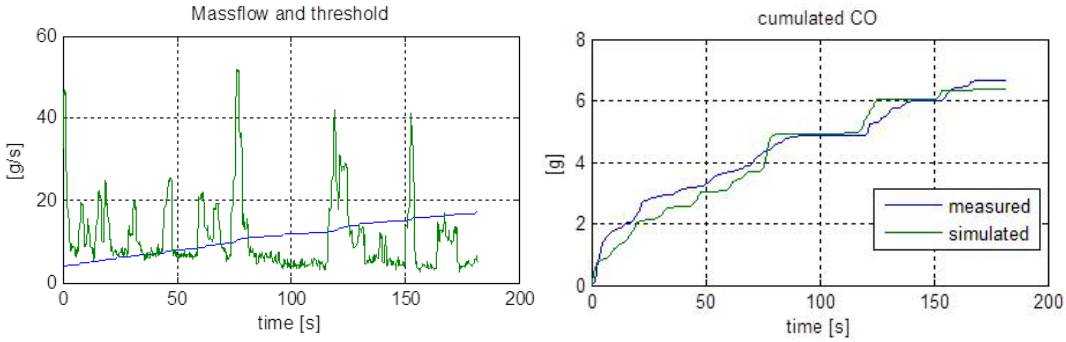

Figure 4: Illustration of model approach for second period of warm up: Left: exhaust gas mass flow (green) and threshold (blue) below which conversion is good. Right: cumulative CO-CSEE that rise as long as exhaust gas mass flow is above threshold (same vehicle and driving cycle as in Figure 1).

For the situation of short time parking the cool down of engines and catalysts is modelled. Data of four cars and 15 cool down situations at different ambient temperatures and wind situations resulted in the following model approaches. The drop of engine temperature depends linearly on the difference of engine and ambient temperatures while the drop of catalyst temperature depends on the difference of these temperatures to the power of 3.8. Catalyst cool down is roughly five times faster than engine cool down (Weilenmann et al., 2012).

Results

Overall, the new model to predict CSEE of pollutants and CO_2 (and cold start extra fuel consumption) consists of 28 parameters per vehicle, considerably less than the 36 parameters of the older empirical model (Weilenmann *et al* 2009). All parameters of engine and emission sub-models may be identified automatically from a minimum of two repetitive cold start tests at two different ambient temperatures. In contrast to the old empirical model, the new model achieves the following qualities: it is applicable to different driving situations. Measurement error (within repeatability) is partly levelled out by the method. Any combination of reduced stop time and ambient temperatures is possible and consistent.

Figure 5 shows CSEE of CO_2 and HC of different cycles at 23 °C as well as for two cycles over different ambient temperatures. In the upper plots cycles are ordered according to average load. While CO_2-CSEE rise clearly with higher loads, HC-CSEE depend on average load as well as on cycle dynamics (being elevated in IUFC15 and IRC15 cycles). The CSEE of CO_2 at -17 °C are four times higher than those at 23 °C. However, HC-CSEE at -17 °C are ten times higher than at 23 °C.

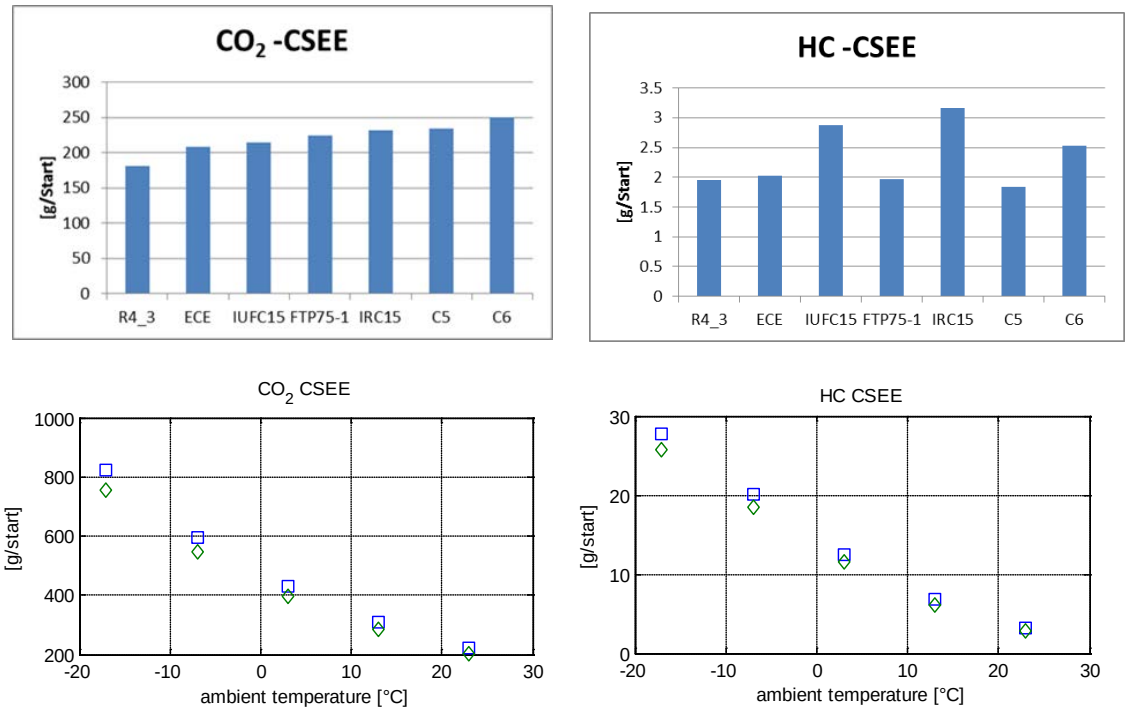

Figure 5: Model results: Top row: CSEE in function of different cycles at 23 °C (Cycles: 1 = R4-3: a stop and go cycle (Stettler et al., 2004). 2 = ECE: urban part of European homologation cycle. 3 = IUFC15: real world urban cycle (Andre, 2004). 4 = FTP-75 part one: first part of US homologation cycle. 5 = IRC15: real world rural cycle (dynamic) (Andre, 2004). 6 = C5: real world rural cycle (higher load) (Weilenmann, 2001). 7 = C6: motorway cycle (Weilenmann, 2001)). Bottom row: CSEE in function of ambient temperature for two cycles (blue squares: IRC15; green rhombs: IUFC15).

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