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Impact of driving dynamics in RDE test on NO_x emissions dispersion

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Abstract

EU6D emission regulation intends to bridge the gap between laboratory tests and the real driving conditions by the introduction of Real Drive Emission (RDE) testing. It requires the measurement of RDE as an additional type approval test in order to take into account the influence of the road profile, ambient conditions and traffic situations. An important amendment has been included in Commission regulation (EU) 2016/646, limiting the driving dynamics and hence avoiding the biased testing of the vehicle.

In this work, a drive cycle generator has been developed to synthesize cycles meeting all the regulatory requirements of the RDE testing. The generator is based on the transition probability matrix obtained from each phase of the WLTP cycle. Driving dynamics have been varied based on RDE regulations and several trips have been generated with dynamics ranging from soft to aggressive. A Direct Injection Compression Ignition (DICI) 1.5L engine with a state of the art aftertreatment system has been utilised to run the generated synthetic cycles. The analysis of the results obtained in the tests (all of them complying with RDE restrictions in terms of driving dynamics) points out a noticeable 60% relative dispersion in the NO_x emissions downstream of the catalyst.

The contribution of the proposed method lies not only in the fact that it synthesises driving cycles as stochastic process and is capable of tuning the driving dynamics based on RDE regulations, but it also presents the range of dispersion possible in NO_x emissions solely due to the driving dynamics. The methodology followed in the present work could be an essential step in future engine developments, where testing engine prototypes on the entire range of driving dynamics in the engine test bench facility could provide interesting insights about the expected NO_x emissions in RDE testing.

Keywords

Real drive NO_x emissions, Drive cycle generator, Driving dynamics

Introduction

Diesel-based road transport is found to be a major cause of European urban air pollution. According to Nils et. al[1] the transportation sector is shown to be responsible for 46% of the total NO_x emissions. As per EU comission regulations[2], 80% of these emissions are shown to originate from diesel-powered cars, vans, trucks and buses. Vehicular emissions for European passenger cars have been regulated by means of the European emission standards since 1992. In this way, the European Union (EU) has enforced the type-approval process based on the representative cycles like New European Driving Cycle (NEDC) and more recently World harmonised Light vehicle Test Procedure (WLTP). Nevertheless, according to Chen Yuche and Jens[3], NO_x emissions by European diesel cars are shown to have not decreased at all, despite the continuous tightening of the NO_x type approval limits from EU1 to EU6. The author highlights that the difference between type approval NO_x and real-world NO_x has grown significantly over the years and compared to the current type approval limit value of 0.080 g/km, real-world NO_x emissions as shown by the author in[4] are found to be even more than 0.32 g/km, these differences have been shown by many authors like in Samuel et. al in[5] and by Zacharof et. al in[6].

RDE tests under real driving conditions poses a major challenge for the OEMs since the situational environmental conditions such as temperature, traffic and the behaviour of the driver are not reproducible. As to investigate influences of hardware and software on the emission performance, constant or at least, reproducible conditions are necessary. The challenges in meeting RDE requirements are most pressing in early development stages. This has created demand for alternative means of ensuring product compliance early in the development process without the need for costly on-vehicle testing, and the engine testing is an important solution to understand effect of such uncertainities. The disperion for WLTP cycle due to ambient temperature has been shown by Luján et al. in[7]. On the similar lines the impact of driving dynamics is investigated using an engine test bench facility. In particular, this article presents a real drive NO_x emission study using a drive cycle

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generator capable of creating synthetic routes with variable driving dynamics and fulfilling RDE testing protocols. The routes are later tested in an engine test bench.

State of the art for construction of synthetic drive cycles is to randomly append driving segments, where a segment is a driving sequence between two stops as demonstrated by Michel in[8]. An issue with such a method as mentioned by Jie and Debbie in[9], is that it gives no consideration for differentiation in modal events (e.g. cruise, idle, acceleration and deceleration) and also there is no way to set the length of the cycle. In[9], Jie and Debbie proposes to use a stochastic process for binning of data until certain statistical criterias are met. The bins are based on which modal event they belong to and are extracted from the measured driving cycles. However, due to the size of these snippets, it is still difficult to achieve the desired driving distance and at the same time obtain driving cycles that are representative of real driving. Another way would be to generate single velocity and acceleration states at any instant, instead of the entire bin. One option is to generate driving cycles by using Markov chains, as described in[10]. This includes extracting information from a database of real-world traffic, analysing the data and to generate driving cycles from a stochastic process. Following this approach, the present work generates synthetic drive cycles by binning the WLTP cycle in three phases (urban, rural and motorway) and using a Markov like process, while validating the cycles using RDE regulations. Moreover, in the article[11] by Gong et. al, the Markov chain approach is shown to be the most popular method for generating representative driving cycles.

In the article by Francois et. al[12], a considerable dispersion has been reported in the driving dynamics of average drivers and vehicles. The dynamics are found to exceed the upper boundary limits, defined in equation 7. In the article[13] by Josh et. al it has been shown that the driving conditions (including unusually cold or hot ambient temperatures, driving dynamics, driving at high speeds, driving at higher altitude and diesel particulate filter regeneration events) not covered by the RDE test are to have a relatively high contribution to overall NO_x emissions. The authors suggest the requirement of new boundary conditions to be enforced in the future regulation.

As a matter of fact, driver monitoring and driver style correction can improve fuel economy. According to Rajan et. al in[14], driver style and driving events like city and highway driving both affects vehicle energy demand. Hence both have to be considered in developing a vehicle. A lot of work is focused towards improving driver style by providing driver assist both in conventional vehicles as shown by the Guenter et. al in[15] and for HEVs as shown by the authors in[16]. Indeed, in past the researchers have been trying to assess the effect of driving behaviour on vehicle performance, however with the advent of new RDE regulations, it has become even more interesting for researchers.

The dispersion in NO_x emissions produced by a vehicle, by variation in trip characterstics (average speed in each phase, trip composition, dynamics etc.) within the regulation limits draws attention of the authors. Consideration of this dispersion is indispensible during the vehicle development and therefore to achieve RDE objective the manufacturer must develop his vehicle calibration for the worse case scenario within the trip specific regulatory limits and the regulators must include it during type approval testing. To achieve that, the present article proposes a method to assess the contribution of randomness in trip charaterstics on the dispersion in NO_x emissions, which is critical for both vehicle development and type approval process. The different driving styles have been characterized by driving parameters, such as relative positive acceleration by Gallu et. al in[17]. To study the combined real driving conditions, Mierlo et. al in[18] measured emissions in small driving cycles, representative of a certain traffic situation or driving style, and repeated them on a roll-bench to measure the emissions in controlled circumstances. These studies require lot of measured data in order to simulate the real conditions, which could be difficult to achieve during intial engine development phases.

The proposed method is not only capable of synthesising driving cycles as stochastic process and is tuning the driving dynamics based on RDE regulations, but it also presents the range of dispersion possible in NO_x emissions solely due to the driving dynamics for powertrain fitted with state of the art aftertreatment system. The methodology followed in the present work could be an essential step in the future engine developments, where testing engine prototypes over the entire range of driving dynamics in the engine test bench facility could provide interesting insights about the expected NO_x emissions in real drive emission testing. The present work also provide some suggestions to the legislators for future emission norms. The rest of the paper proceeds as follows: section 2 presents a brief summary of EU6D emission norms. The following section presents the procedure to synthesise drive cycles within regulations and the resulting cycles with different driving dynamics. Section 4 briefly presents experimental setup, the next section presents the results and analysis of the trip dynamics and dispersion in the NO_x emission for all the synthesised cycles. Finally the work has been summarised in section 6.

EU6D Regulations

To eliminate the difference between declared and real emissions, EU6D regulations for light duty vehicles complement the dynamometer based type approval procedure with on road emission testing by means of portable emission measurement devices. The new regulations expect significant reduction in emissions, especially in metropolitan areas as RDE limits apply for the urban part of a RDE trip as for the entire trip. To allow a progressive adaption of vehicle manufacturers to the new situation, the Conformity Factors (CF) leading to the maximum emission limits for RDE will be introduced in two phases. Temporarily CF_{NO_x} is 2.1 and from 2020, it will be decreased to 1.5. Accordingly, not to exceed limits (NTE) for real drive NO_x emission has been fixed to:

$$NTE_{NO_x} = CF_{NO_x} \times EU6_{NO_x} \tag{1}$$

where, $EU6_{\mathrm{NO}_x}$ represent the Euro 6 limit for NO_x emissions, which is 0.08g/km.

For a trip to be qualified for RDE type approval, it is required to have certain characterstics as listed in table 1

Table 1. Regulatory requirements

Altitude	0 to 700 m (Ext: 700 to 1300 m) cum. elevation 1200m/100km
Alt. difference	<100 m between start and end
Ambient temp.	Moderate: 0C to 30 C (Ext: -7C-0C and 30C-35C)
Dynamics	Max:$v.a_{pos}$ Min:RPA
Maximum speed	145 km/h(>100km/h for 5min)
Payload Maximum	90% of the max vehicle weight

Table 2. Trip Characteristic Requirements

Average Speeds	Urban	15 to 40 km/h
	Rural	< 60 km/h
	Motorway	> 90 km/h
Distance	Urban	> 16 km
	Rural	> 16 km
	Motorway	> 16 km
Trip Composition	Urban	29 % to 44%
	Rural	23 % to 43%
	Motorway	23 % to 43%
Total Trip Duration	-	90min to 120 min
Stop %	-	6-30% of urban

and it must also be within certain boundary conditions as summarized in table 2.

An RDE trip must cover three phases: urban u, rural r and motorway m. These phases are based on vehicle speed: a vehicle travelling up to 60km/h will be considered to be operating in urban conditions; at 60 to 90 km/h in rural and above 90km/h in motorway conditions. The trip is then binned (in phases) for assessment of the dynamics in each phase. The RDE regulation as in the document[2], defines a lower and an upper boundary condition for the driving dynamics in each phase. This is in order to ensure that the vehicle is not driven in an excessively soft or aggressive style.

An excessively soft driving that would lead too low and non realistic NO$_x$ emissions is eliminated by lower boundary limits defined for Relative Positive Acceleration (RPA) as in equation 2, which is defined as the integral of vehicle speed (v) multiplied with the time step and the positive acceleration(a_{pos}) for all accelerations $> 0.1\ m/s^2$, divided by the total distance of the cycle(d).

$$RPA_k = \frac{\sum_j [dt \cdot (v.a_{pos})_{j,k}]}{\sum_i d_{i,k}} \tag{2}$$

where i=1 to N_k; j=1 to M_k; k = $\{u,r,m\}$, RPA_k is the relative positive acceleration for u, r and m phases, dt is the time step equal to 1 second, M_k the sample number with positive acceleration in each phase and N_k is the total sample number in each phase.

An excessively aggressive driving will be eliminated by upper boundary limits defined for the 95^{th} percentile of the product between actual vehicle speed and positive acceleration($> 0.1\ m/s^2$) for each phase, denoted as $(v.a_{pos})_{k\_95}$.

The upper and lower boundary limits are defined as in equations 7, any of these condition makes a trip invalid. Where, $\bar{v}_k$ is the average velocity in a phase.

$$\begin{aligned}
&for\ \bar{v}_k < 74.6\ [\text{km/h}];if\ (v \cdot a_{pos})_{k\_95} > (0.136.\bar{v}_k + 14.44)\\
&\quad or\\
&for\ \bar{v}_k > 74.6\ [\text{km/h}];if\ (v \cdot a_{pos})_{k\_95} > (0.0742 \cdot \bar{v}_k + 18.966)\\
&\quad or\\
&for\ \bar{v}_k < 94.05\ [\text{km/h}];if\ RPA_k < (-0.0016 \cdot \bar{v}_k + 0.1755)\\
&\quad or\\
&for\ \bar{v}_k > 94.05\ [\text{km/h}];if\ RPA_k < 0.025
\end{aligned} \tag{3}$$

Synthetic drive cycle generator

In the current study, the synthesis procedure uses Markov chain due to its relative simplicity in representing an unknown system. Markov property means that the future states depend only on the present states and are independent of the past states. Let the state $x_n = v_n$ where v_n is the current velocity. A Markov chain is a sequence of random variables X_1,X_2, ...X_n whose conditional probabilities are expressed as;

$$\begin{aligned}P(X_{n+1} = x_{n+1}|X_1 = x_1, X_2 = x_2, \ldots, X_n = x_n)\\ = P(X_{n+1} = x_{n+1}|X_n = x_n)\end{aligned} \tag{4}$$

The set of possible values that the random variables X_n can take is called the state space of the chain. The conditional probabilities are called transition probabilities. The sum of all probabilities leaving a state must satisfy:

$$\sum_j p_{ij} = \sum_j P(X_{n+1} = j|X_n = i) = 1 \tag{5}$$

and p_{ij} is predicted by all such transitions that have occurred in each phase of the WLTP cycle. The probability used in the synthesis procedure is time independent or time homogeneous, that is, as time goes on, the probability of moving from one state to another may changes. In other words, knowledge of the previous state is all that is necessary to determine the probability distribution of the current state. All the transition probabilities are stored as a Transition Probability Matrix for each phase. In the present work the vehicle speed has been taken as the system state (x_n = v_n) and its sequence in each phase of the WLTP has been used to build the Transition Probability Matrices. For practical reasons, the data has been discretised in steps of 1 km/h in velocity. The process of cycle synthesis could be summarised as :

Step 1: Transition probability matrices (TPM_k), where k represents the phase have been extracted from each phase of the WLTP cycle as shown in figure 1. In particular, the probabilities are assumed to be equal to the event frequency during a given WLTP phase. In this way, statistical properties of each phase of WLTP are retained, for example the low motorway drive dynamics and the speed range (0 to 120 km/h) have been retained during the synthesis itself. Moreover, synthesis by this method results in cycles whose dynamics are within the protocol boundaries defined in equation 7.

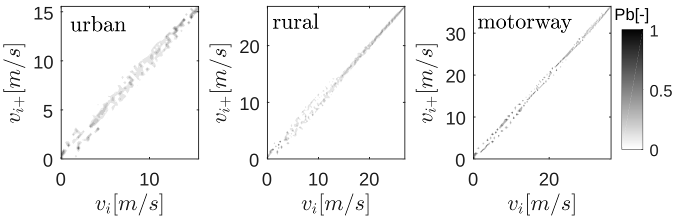

Figure 1. Speed transition probabilities from current speed v_i to v_{i+} in the urban, rural and motorway phase

It can be noted, that according to the selection of velocity as state, distance between the zero probability entries and the main diagonal in figure 2 is an indicator of the cycle aggressiveness. In fact, this distance is a measure of the attainable acceleration since it provides a boundary on the difference between the actual and the next vehicle speed. This property has been used to vary the cycle aggressiveness during the synthesis, since the wider the non-zero values near the main diagonal of the transition matrix, more aggressive the driving cycle becomes. An example has been shown in figure 2 for the urban phase of the cycle.

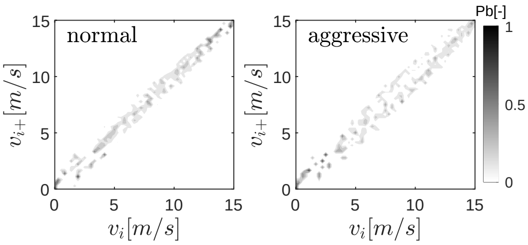

Figure 2. Speed transition probabilities from current speed v_i to v_{i+} in the urban phase, with normal and high aggressiveness

Step 2: The inputs to the generator are the initial vehicle velocity (v_0), total time (T) and the Cumulative Probability Function ($CPF_{i,k}$) derived from phasewise TPM_k extracted in **Step 1**. The generator randomly allots a time for each phase, such that $\sum_{k=u,r,m} t_k = T$ and fulfilling with composition requirements in table 2. Then the synthesis of each phase is dealt with separately. The corresponding $CPF_{i,k}$ is used to randomly generate velocity for the next time step. Later the three phases are merged to form the entire cycle.

This step is illustrated with an example in figure.3. For instance the initial velocity v_0 is 17 km/h. The generator randomly generates a probability i.e. 0.98 and uses the cumulative probability function $CPF_{i,k}$ for i=17 km/h and selects accordingly the velocity for next time step i.e. 19.7 km/h (20 km/h, nearest integer). Then, in the next iteration, a CPF value is randomly generated (0.85) and similarly it predicts 22 km/h for the next time step. This process continues for t_k steps, and the then switches to a new TPM_k which is based on the different phase. At time T a deceleration phase is imposed using the CPF_k allowing a natural stopping of the vehicle. In order to eliminate speed fluctuations at very low vehicle speed and to have minimum stopping time as per RDE regulation, a filter has been applied which ensures the vehicle is brought to rest for 10 s (a regulation requirement) if the generator brings down the velocity to 5 km/h.

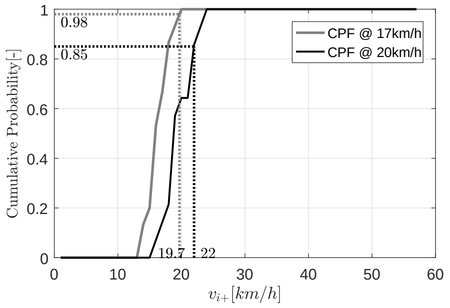

Figure 3. Illustration of velocity generator in urban phase

Step3: The generated trip is validated for the statistical requirements of RDE regulations mentioned in table 2 in a loop and the qualified trips are retained for the analysis. The validation of dynamics as in equation 7 is graphically represented in figure 4. Each urban, rural and motorway section of the cycles must be below the line showing speed multiplied by positive acceleration and above the line showing relative positive acceleration (RPA).

Using the transition probabilities of figure 2, several synthetic drive cycles have been generated, dynamics of which are shown in figure 4.

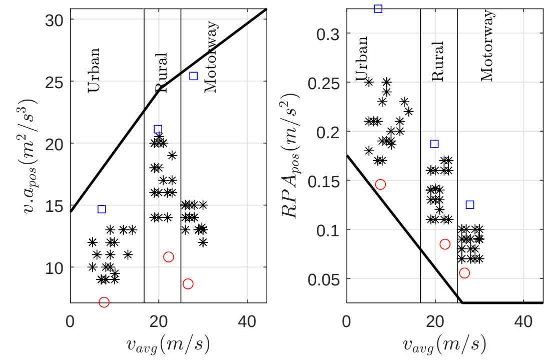

Figure 4. High and low dynamic boundaries; Synthetic trips within RDE protocol, ○ is soft, $*$ are standard, □ is aggressive compared to WLTP dynamics

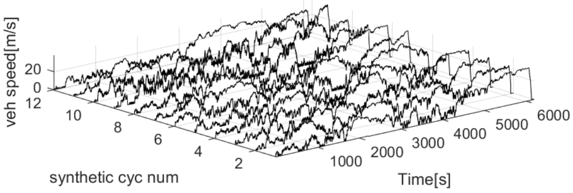

Figure 5. Set of synthesised cycles

The proposed method is able to synthesize driving cycles fast (0.26 s in a standard computer) and within regulatory trip characterstics. A few driving cycles have been shown in figure 5. The charactristics of a driving cycle can be classified according to several criteria, such as the speed trajectory, the operating modes (idling, cruising,...), the vehicle mass, the temperature, the altitude or the alttitude gain. Most of them are covered by the RDE regulation in[2], and amongst them, the driving dynamics (sequence of vehicle speed and acceleration) play a key role, also presented by author in[19]. The sequence of vehicle speeds and acceleration is unique for a given driving cycle, but their dynamics can be captured by a set of parameters as shown by Ericsson in[19], the regulation also considers two of them (RPA and $(v.a_{pos})$). The proposed method assures that the set of driving cycles generated keep the dynamic paremeters so despite differences in the sequence of vehicle speed, the driving cycle dynamics will be comparable. Moreover, the method is able to include aggressiveness in the synthesis process, and it is therefore widely applicable to study the impact of dynamics on emissions and fuel consumption. These cycles are run in an enigne test bench facility, as explained in the following section, for assessing the impact of driving dynamics on NO$_x$ emissions.

Experimental Setup and emission measurements

Consistent testing conditions are necessary to investigate separately the effect of changes in hardware, software and driving conditions. To obtain realistic engine operating conditions a validated vehicle model based on longitudinal vehicle dynamics has been used, the model solves the Newton equation at each time step to obtain the vehicle acceleration from the balance between traction and resistive forces (or torques). In this sense, the main terms participating in the energy balance of the vehicle model are:

- A source term representing the net torque coming from the engine, including powertrain efficiency and gear transmission ratio.
- An inertial term including vehicle mass and powertrain inertia.
- A set of sink terms taking into account road grade resistance and non-conservative forces, mainly friction loses due to aerodynamic drag and rolling resistance.

The obtained trajectories of engine speed and torque are run on the following engine test setup.

Engine test setup- A DICI 1.5 L diesel engine with specifications as in table 3 has been used for the experiments. The engine is equiped with a state-of-the art aftertreatment system comprising of Diesel oxidation Catalyst, Diesel Particulate Filter and Selective catalytic reduction system. NO$_x$ has been measured before and after the aftertreatment system.

Table 3. Engine specification

Stroke x Bore[mm]	84.8 x 75
Displacement[cc]	1498
Compression ratio	16:1
Number of Cyl	Inline 4
Valves per Cyl	4
Rated Torque	300Nm @ 1750rpm
Emission std.	Euro 6

The engine is coupled to an asynchronous Horiba DYNAS 3 dynos, which is able to perform steady-state, transient and dynamic tests, and it is controlled with a Horiba SPARC, which is controlled at the same time with the PC interface Horiba STARS. The test bench apparatus such as the fuel balance FQ2100 and the gas analyzer (GA) Horiba MEXA 7100 series are connected to the STARS interface. The NTC sensors and the Cambustion NDIR 500 gas analyzer are connected to the RPS dSpace by analogic signal, while the NO$_x$ sensors are connected to the RPS dSpace by CAN protocol. Regarding the data recording, the use of different systems to record data implies that three different files are obtained for each experiment in this setup i.e. from dSpace, STARS and ETAS. In order to be able to phase the different files afterwards, the RPS dSpace triggers a square signal, which allows phasing them in post-processing. For the concentrations measurements in the test bench, the Horiba MEXA 7100 DEGR GA is used to measure NO$_x$ at one point of the exhaust line. For this reason, several tests are repeated in order to have the gas concentrations measurements up- and downstream of the aftertreatment. This apparatus employs techniques like the non-dispersive infrared (NDIR) for the NO$_x$ measurement.

Analysis of the effect of RDE cycle dynamics on NO$_x$ emissions

To study the dispersion of NO$_x$ emissions a set of drive cycles have been selected, the set is of 20 cycles ranging from low to high aggressiveness, synthesised using the developed too having trip charaterstics within the EU6D protocols defined in tables 1 and 2.

Synthetic cycles The engine described in table 3 has been used to run 20 drive cycles to measure NO$_x$ emissions. As an example, in figure 6 the evolution of accumulated NO$_x$ emissions has been plotted before and after the SCR of three driving cycles with different aggressivenes. Clearly the aggressive cycle has higher cumulative emissions compared to the softer ones.

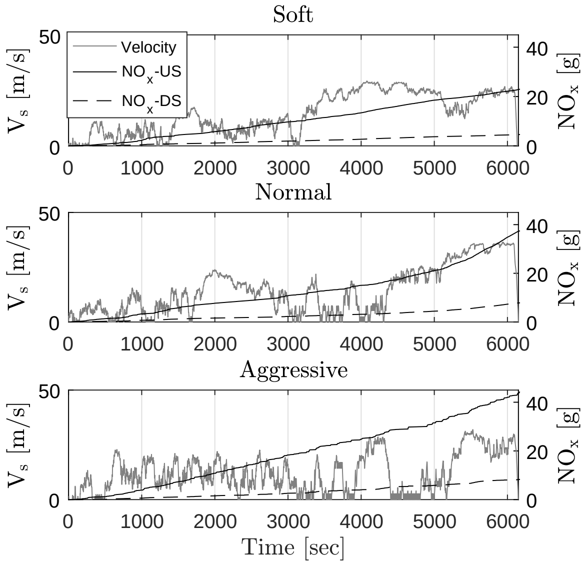

Figure 6. NO$_x$ emissions for three RDE cycles soft, normal and aggressive

In figure 7, the engine perspective has been shown, the main difference in the frequency of engine operations is in the low and high engine speed and load conditions. The spread is higher in the aggressive driving

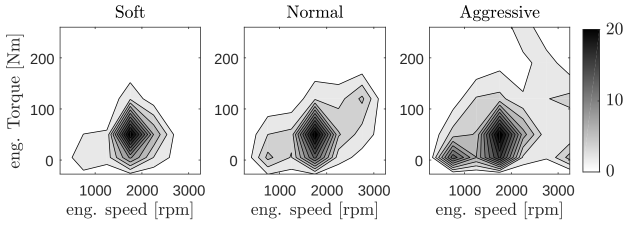

Figure 7. Frequency(%) of engine operation in Soft, Normal and aggressive driving

Dispersion of NO_x emissions for the entire range of driving dynamics is presented in figure 8. Normal distribution curve has been fitted for the sake of readability. This figure also presents the distribution of NO_x emissions for WLTP cycle (run 10 times) in order to separate out the errors occuring due to inconsistencies in the measurements.

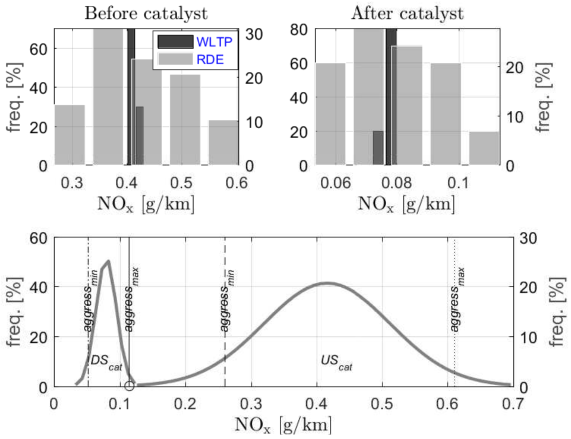

Figure 8. Dispersion in measured NO_x emissions for 20 synthetic cycles before and after catalyst

The dispersion in figure 8 can be used to infer the following:

- Before the catalyst, relative difference in the spread of the bell curve is 100%. In terms of the range, spread is 0.3 g/km for the given vehicle. After SCR, the relative difference is 60% and the range is 0.09g/km, which is in the range of Euro 6 NO_x limits, i.e. 0.08 g/km.
- For the synthetic cycles, minimum and maximum NO_x emissions are equal to 0.115 g/km and 0.06 g/km respectively. It must be noted that the minimum NO_x produced is for the least aggressive cycle and the maximum is for the most aggressive cycle. Indicating that, the tests closer to the lower dynamic limit in the RDE regulation could produce NO_x emissions even lower than the regulation limits.
- It can be inferred that by using aftertreatment system we not only reduce the absolute NO_x emissions but also reduce the range of dispersion occuring due to cycle dynamics.
- For the WLTP cycles the relative dispersion and range is less than 5% and 0.02g/km respectively before the catalyst and the relative dispersion and range is less than 2% and 0.002g/km after the SCR. This indicates the dispersion plotted in the figure has negligible influence of measurement inconsistencies. It can be observed that there exists a few RDE cycles which have emissions even lower than WLTP.

In order to see the trend of emissions due to dynamics, two variables- $(v \cdot a_{pos\_95})_{avg}$ and $(RPA_k)_{avg}$ are defined as an average of trip dynamics in equations 6 and 7.

$$(v \cdot a_{pos\_95})_{avg} = \frac{\sum_{k=1}^{3}[(v \cdot a_{pos})_{k\_95}.t_k]}{\sum_{k=1}^{3}[t_k]} \tag{6}$$

$$(RPA_k)_{avg} = \frac{\sum_{k=1}^{3}[(RPA)_k.t_k]}{\sum_{k=1}^{3}[t_k]} \tag{7}$$

For all the drive cycles the average trip driving dynamics and NO_x emissions have been clustered in figure 9. The results in this figure show that the driving dynamics play a key role on NO_x emissions, so aggressive cycles tend to have higher NO_x emisions. However, there are other parameters that also affect NO_x and are outside the scope of the present study, i.e. one may think that two driving cycles, despite completely equal in the velocity sequence will go through different areas in the engine map if there are differences in the gear selected, so there will be differences on NO_x emissions.

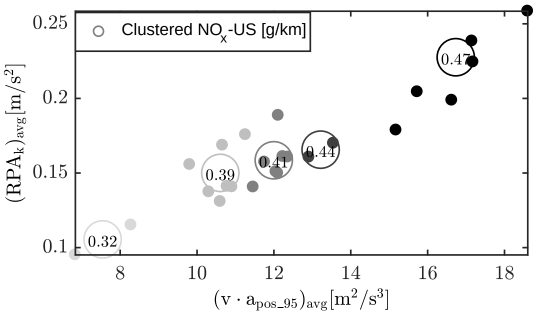

Figure 9. Clusters of NO_x emissions for varying driving dynamics

Finally, phase wise NO_x emissions are plotted in figure.10, the urban drive is seen to have maximum contribution in the overall NO_x emissions.

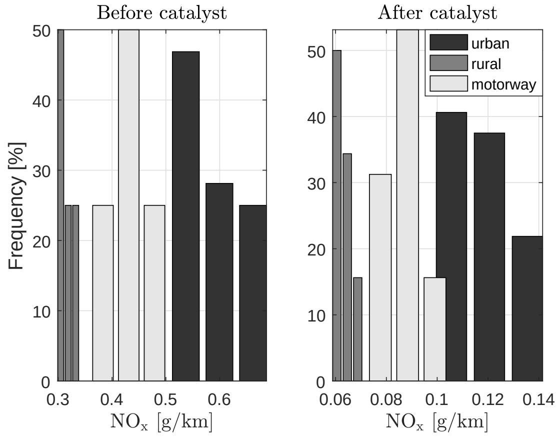

Figure 10. Phase wise distribution of NO_x emission for synthetic cycles

In the urban phase, the relative difference obtained after catalyst is about 30% and the range is approximately 0.13 g/km, which is considerably high, considering exclusive limits on NO_x emisssions in urban phase in EU6D norms. The regulation already demands 50% driving to be done by Type Approval Authority, which reduces the risk of biased driving style. this can be improved by demanding 50% driving by TAA in each phase of the trip especially in urban phase.

Summary/Conclusion

A real drive cycle generator based on velocity transition matrix obtained from the WLTP cycle has been developed. The method is found to be consistent and fast in producing synthetic drive cycles. The novelty of the method is its capability of being able to generate variable driving dynamics based on EU6D regulation. The driving dynamics have been varied within the regulatory limits, in order to achieve a spread of NO_x emissions. Therefore, during the development phase of any vehicle the presented cycle synthesis tool accompanied with an engine test bench facility would be very useful tool to have a sense of required engine calibration in order to reduce the risk of failure during the Type approval.

With the existing vehicle and within the RDE cycle characteristic protocols, a considerable spread in the NO_x emissions is observed. The spread is shown to be majorly due to trip composition and driving dynamics. Increase in the share of urban drive and driving aggressiveness is shown to increase cycle NO_x emissions. The EU6D regulation which mandates the vehicle to pass emission norms individually in urban phase is an appropriate control and an additional control over urban driving style will definitely improve the confidence in the estimation of real drive emissions. The regulation already demands 50% driving to be done by Type Approval Authority, which reduces the risk of biased driving style, can be improved by demanding 50% driving by TAA in each phase of the trip. Considering that this dispersion arises solely due to cycle dynamics, the dispersion is sigficantly high.

Phasewise distribution of NO_x emission shows that the driving in urban phase is the bottleneck in emission control because the dispersion during this phase is found to be maximum. Therefore, the existing dynamic boundary limits may not be enough to estimate real drive emissions, especially during urban drive.

NO_x emitted for entire cycles is in the lower range and therefore the regulatory dynamic boundaries are appropriate for the NO_x estimation for the given vehicle. However the dispersion indicates that even if the vehicle stays well within the boundaries, the NO_x emissions declared in an experiment may be a conjecture and fails to predict the real drive emissions for several trip within the protocol, especially during the urban phase.

The obtained dispersion is solely due to the variation in trip characteristics within the EU6D protocols, that is, even if the bell curve were to move leftwards, any method to account for the dispersion during engine calibration will remain a major challenge. But for real driving conditions, estimation of driving style and adaptive calibration, proposed by the author in[20] could be a sought after solution to obtain close to optimal engine controls while staying within the regualtory limits.

Moreover, it is necessary to address the dispersion in NO_x emissions due to trip dynamics in the future regulations. Wider spread compared to the well defined drive cycles, like NEDC/WLTP seems unavoidable even with RDE regulations. Consideration of dispersion during the type approval will definitely reduce the difference between declared emissions and real drive emissions. Without which, the new RDE regulations may undermine its own objective which is to eliminate the gap between declared and real emissions.

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References

1. Nils H, Maarten M, Joeri V et al. A review of the European passenger car regulations – Real Driving Emissions vs local air quality. *Elsevier Ltd* 2018; .
2. Commission regulation EU 2016/646 of 20th april 2016 amending regulation EC No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro6), 2016.
3. Yuche C and Jens BK. Real-driving emissions from cars and light commercial vehicles – results from 13 years remote sensing at Zurich/CH. *Atmospheric Environment* 2014; .
4. Veerle H, Gerrit K, Norbert L et al. NOx emissions of fifteen euro 6 diesel cars: Results of the dutch LD road vehicle emission testing programme 2016. Technical report, TNO, 2016.
5. Samuel S, Morrey D, Fowkes M et al. Real-world fuel economy and emission levels of a typical euro-iv passenger vehicle. proceedings of the institution of mechanical engineers. *Part D: Journal of Automobile Engineering* 2005; .
6. Zacharof N, Tietge U, Franco V et al. Type approval and real-world co2 and nox emissions from eu light commercial vehicles. *International Council on Clean Transportation, Germany* 2016; .
7. Luján JM, Climent H, Ruiz S et al. Influence of ambient temperature on diesel engine raw pollutants and fuel

consumption in different driving cycles. *International Journal of Engine Research* 2018; .

8. Michel A. Driving cycles development: Characterization of the methods. *SAE Technical Papers* 1996; .
9. Jie L and Debbie N N. An exploratory analysis comparing a stochastic driving cycle to California's regulatory cycle. *Atmospheric Environment* 2002; .
10. TK L and ZS F. Synthesis of real-world driving cycles using stochastic process and statistical methodology. *International Journal of Vehicle Design* 2011; .
11. Gong Q, Midlam MS, Marano V et al. An iterative markov chain approach for generating vehicle driving cycles. *SAE International Journal of Engines* 2011; .
12. François C. Real world fuel economy measurements. Technical report, groupe PSA, transport and environment, France nature environnement (FnE) and Bureau Veritas, 2017.
13. Josh M and Vicente F. Impact of improved regulation of real-world NOx emissions from diesel passenger cars in the EU 2015 2030. Technical report, International Council on Clean Transportation, 2016.
14. Rajan BVP, McGordon A and Jennings PA. An investigation on the effect of driver style and driving events on energy demand of a PHEV. *World Electric Vehicle Journal Vol 5* 2012; .
15. Günter Reichart S, Claus D, Heinrich R et al. Potentials of BMW driver assistance to improve fuel economy. *FISITA 1998 World Automotive Congress* 1998; .
16. Fazal S, SN AD, Carrie G et al. Design and analysis of an adaptive realtime advisory system for improving real world fuel economy in a hybrid electric vehicle. *SAE Journal* 2010; .
17. Gallus J, Kirchner U, Vogt R et al. Impact of driving style and road grade on gaseous exhaust emissions of passenger vehicles measured by a portable emission measurement system (pems). *Transportation Research Part D: Transport and Environment* 2017; .
18. Mierlo JV, Maggetto G, Burgwal EV et al. Driving style and traffic measures-influence on vehicle emissions and fuel consumption. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 218(1), 43–50* 2004; .
19. Ericsson E. Independent driving pattern factors and their influence on fuel-use and exhaust emission factors. *TRANSPORT RESEARCH PART D* 2001; .
20. Guardiola C, Pla Moreno B, Bares-Moreno P et al. Adaptive calibration for reduced fuel consumption and emissions. *Journal of Automobile Engineering* 2016; .