Impact of driving dynamics in RDE test on NO\textsubscript{x} emissions dispersion

José Manuel Luján\textsuperscript{1} , Carlos Guardiola\textsuperscript{1} , Benjamín Pla\textsuperscript{1} , Varun Pandey\textsuperscript{1}

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\textsubscript{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\textsubscript{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\textsubscript{x} emissions in RDE testing.

Keywords

Real drive NO\textsubscript{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\textsuperscript{1} the transportation sector is shown to be responsible for 46% of the total NO\textsubscript{x} emissions. As per EU comission regulations\textsuperscript{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\textsuperscript{3}, NO\textsubscript{x} emissions by European diesel cars are shown to have not decreased at all, despite the continuous tightening of the NO\textsubscript{x} type approval limits from EU1 to EU6. The author highlights that the difference between type approval NO\textsubscript{x} and real-world NO\textsubscript{x} has grown significantly over the years and compared to the current type approval limit value of 0.080 g/km, real-world NO\textsubscript{x} emissions as shown by the author in\textsuperscript{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\textsuperscript{5} and by Zacharof et. al in\textsuperscript{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 uncertainties. The dispersion for WLTP cycle due to ambient temperature has been shown by Luján et al. in\textsuperscript{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\textsubscript{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. An issue with such a method as mentioned by Jie and Debbie 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 , 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. 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 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, 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 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\textsubscript{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, 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 and for HEVs as shown by the authors in. 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\textsubscript{x} emissions produced by a vehicle, by variation in trip characteristics (average speed in each phase, trip composition, dynamics etc.) within the regulation limits draws attention of the authors. Consideration of this dispersion is indispensable 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 characteristics on the dispersion in NO\textsubscript{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. To study the combined real driving conditions, Mierlo et. al in 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 initial 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\textsubscript{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\textsubscript{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\textsubscript{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 $CF_{\text{NO}x}$ is 2.1 and from 2020, it will be decreased to 1.5. Accordingly, not to exceed limits ($NTE$) for real drive NO\textsubscript{x} emission has been fixed to:

$$NTE_{\text{NO}x} = CF_{\text{NO}x} \times EU6_{\text{NO}x}$$

where, $EU6_{\text{NO}x}$ represent the Euro 6 limit for NO\textsubscript{x} emissions, which is 0.08g/km.

For a trip to be qualified for RDE type approval, it is required to have certain characteristics as listed in table 1.
Table 1. Regulatory requirements

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

Table 2. Trip Characteristic Requirements

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speeds</td>
<td>Urban 15 to 40 km/h Rural &lt; 60 km/h Motorway &gt; 90 km/h</td>
</tr>
<tr>
<td>Distance</td>
<td>Urban &gt; 16 km Rural &gt; 16 km Motorway &gt; 16 km</td>
</tr>
<tr>
<td>Trip Composition</td>
<td>Urban 29 % to 44% Rural 23 % to 43% Motorway 23 % to 43%</td>
</tr>
<tr>
<td>Total Trip Duration</td>
<td>90min to 120 min</td>
</tr>
<tr>
<td>Stop %</td>
<td>6-30% of urban</td>
</tr>
</tbody>
</table>

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 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 NOx 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 $> 0.1 \text{m/s}^2$, divided by the total distance of the cycle(d).

$$RPA_k = \frac{\sum_j [dt \cdot (v \cdot a_{pos})_{j,k}]}{\sum_{i} d_i,k}$$ (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 for the 95th percentile of the product between actual vehicle speed and positive acceleration($> 0.1 \text{m/s}^2$) for each phase, denoted as $(v \cdot a_{pos})_{k.95}.$

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.

$$f_{or} \bar{v}_k < 74.6 \text{[km/h]} \text{; } if \ (v \cdot a_{pos})_{k.95} > (0.136 \cdot \bar{v}_k + 14.44)$$

or

$$f_{or} \bar{v}_k > 74.6 \text{[km/h]} \text{; } if \ (v \cdot a_{pos})_{k.95} < (0.0742 \cdot \bar{v}_k + 18.966)$$

or

$$f_{or} \bar{v}_k < 94.05 \text{[km/h]} \text{; } if \ RPA_k < (-0.0016 \cdot \bar{v}_k + 0.1755)$$

or

$$f_{or} \bar{v}_k > 94.05 \text{[km/h]} \text{; } if \ RPA_k < 0.025$$ (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:

$$P(X_{n+1} = x_{n+1} | X_1 = x_1, X_2 = x_2, ... , X_n = x_n) = P(X_{n+1} = x_{n+1} | X_n = x_n)$$ (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:

$$\sum_j p_{ij} = \sum_j P(X_{n+1} = j | X_n = i) = 1$$ (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 the state 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.
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.

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 $TPM_i$ extracted in Step 1. The generator randomly allots a time for each phase, such that $\sum_{k=0}^{n} t_k = T$ 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 then switches to a new $TPM_i$ which is based on the different phase. At time $T$ a deceleration phase is imposed using the $CPF_{i,k}$ 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 1. Speed transition probabilities from current speed $v_i$ to $v_{i+1}$ in the urban, rural and motorway phase

Figure 2. Speed transition probabilities from current speed $v_i$ to $v_{i+1}$ in the urban phase, with normal and high aggressiveness

Figure 3. Illustration of velocity generator in urban phase

Step 3: 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, o is soft, * is 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 characteristics. A few driving cycles have been shown in figure 5. The characteristics 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 altitude 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 parameters 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 engine test bench facility, as explained in the following section, for assessing the impact of driving dynamics on \(\text{NO}_x\) 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 equipped with a state-of-the-art aftertreatment system comprising of Diesel oxidation Catalyst, Diesel Particulate Filter and Selective catalytic reduction system. \(\text{NO}_x\) has been measured before and after the aftertreatment. 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 Camustion NDIR 500 gas analyzer are connected to the RPS dSpace by analogic signal, while the \(\text{NO}_x\) 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 \(\text{NO}_x\) 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 \(\text{NO}_x\) measurement.

**Analysis of the effect of RDE cycle dynamics on \(\text{NO}_x\) emissions**

To study the dispersion of \(\text{NO}_x\) 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 tools having trip characteristics 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 \(\text{NO}_x\) emissions. As an example, in figure 6 the evolution of accumulated \(\text{NO}_x\) emissions has been plotted before and after the SCR of three driving cycles with different aggressivenesses. Clearly the aggressive cycle has higher cumulative emissions compared to the softer ones.

**Table 3. Engine specification**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke x Bore[mm]</td>
<td>84.8 x 75</td>
</tr>
<tr>
<td>Displacement[cc]</td>
<td>1498</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16:1</td>
</tr>
<tr>
<td>Number of Cyl</td>
<td>Inline 4</td>
</tr>
<tr>
<td>Valves per Cyl</td>
<td>4</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>300Nm @ 1750rpm</td>
</tr>
<tr>
<td>Emission std.</td>
<td>Euro 6</td>
</tr>
</tbody>
</table>

**Figure 6. \(\text{NO}_x\) 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 \textsubscript{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 \textsubscript{x} emissions for WLTP cycle (run 10 times) in order to separate out the errors occurring due to inconsistencies in the measurements.

**Figure 8.** Dispersion in measured NO \textsubscript{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 \textsubscript{x} limits, i.e. 0.08 g/km.

- For the synthetic cycles, minimum and maximum NO \textsubscript{x} emissions are equal to 0.115 g/km and 0.06 g/km respectively. It must be noted that the minimum NO \textsubscript{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 \textsubscript{x} emissions even lower than WLTP.

- 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.

\[
(v \cdot a_{pos,95})_{avg} = \frac{\sum_{k=1}^{3}[(v \cdot a_{pos})_k \cdot t_k]}{\sum_{k=1}^{3}[t_k]}
\]

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

For all the drive cycles the average trip driving dynamics and NO \textsubscript{x} emissions have been clustered in figure 9. The results in this figure show that the driving dynamics play a key role on NO \textsubscript{x} emissions, so aggressive cycles tend to have higher NO \textsubscript{x} emissions. However, there are other parameters that also affect NO \textsubscript{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 \textsubscript{x} emissions.

**Figure 9.** Clusters of NO \textsubscript{x} emissions for varying driving dynamics

Finally, phase wise NO \textsubscript{x} emissions are plotted in figure.10, the urban drive is seen to have maximum contribution in the overall NO \textsubscript{x} emissions.
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\textsubscript{x} emissions 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\textsubscript{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\textsubscript{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\textsubscript{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 significantly high.

Phase wise distribution of NO\textsubscript{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\textsubscript{x} emitted for entire cycles is in the lower range and therefore the regulatory dynamic boundaries are appropriate for the NO\textsubscript{x} estimation for the given vehicle. However the dispersion indicates that even if the vehicle stays well within the boundaries, the NO\textsubscript{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 \cite{20} could be a sought after solution to obtain close to optimal engine controls while staying within the regulatory limits.

Moreover, it is necessary to address the dispersion in NO\textsubscript{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.

**Acknowledgements**

The authors acknowledge the support of Spanish Ministerio de Economia, Industria y Competitividad through project TRA2016-78717-R.

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