

# Reduction of Transient Particulate Matter Spikes with Decision Tree Based Control

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## ABSTRACT

Decision trees have been proposed as a basis for modifying table based injection to reduce transient particulate spikes during the turbocharger lag period. It has been shown that decision trees can detect particulate spikes in real time. In well calibrated electronically controlled diesel engines these spikes are narrow and are encompassed by a wider NO<sub>x</sub> spike. Decision trees have been shown to pinpoint the exact location of measured opacity spikes in real time thus enabling targeted PM reduction with near zero NO<sub>x</sub> penalty. A calibrated dimensional model has been used to demonstrate the possible reduction of particulate matter with targeted injection pressure pulses. Post injection strategy optimized for near stoichiometric combustion has been shown to provide additional benefits. Empirical models have been used to calculate emission tradeoffs over the entire FTP cycle. An empirical model based transient calibration has been used to demonstrate that such targeted transient modifiers are more beneficial at lower engine-out NO<sub>x</sub> levels.

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## INTRODUCTION

The diesel particulate filter has been so successful in reducing total particulate mass (PM) from diesel exhaust that engine calibrators often focus almost exclusively on engine-out NO<sub>x</sub> emissions, particularly in the absence of number (PN) limits. This situation is problematic because of a number of reasons. The detrimental health effects of particulate matter and ultrafine particles are well known [1,2,3]. It is evident that DPF's do not get rid of all particles [4], and the trapping efficiency of ultrafine particles of current DPFs might be less than 70% [5], particularly during and shortly after regeneration [6,7,8], when the soot cake has been recently oxidized. DPF trapping efficiencies will increase in the future but will be limited by backpressure and fuel consumption penalties. It is physically impossible to trap all particles without restricting flow significantly. The European standard of  $6 \times 10^{11}$  particles/km limit on new vehicles sold after Jan 2013 [9], reflects the reality of diesel combustion, i.e., even with the most advanced injection and aftertreatment technologies, diesel engines equipped with DPFs are expected to emit billions of particles per km. In addition to health concerns, engine-out PM contributes to global warming by creating backpressure and increasing fuel consumption. Engine out PM and PN reduction is therefore the motivation of the current work.

It is common knowledge that visible diesel smoke is primarily a transient phenomenon and experimental investigations have suggested that the instantaneous peak of particulate concentration can be ten times larger than the corresponding steady state value while up to half of total particulate mass over the urban driving cycle is due to transient spikes [10]. Yet published literature on transient PM reduction constitutes only a small fraction of emission control literature. Published work addressing strategies to control transient PM are even scarcer. The following two paragraphs summarize recent transient PM and PN investigations respectively.

Some researchers including the author have attempted to reduce transient emissions by developing or using model based transient optimization processes [11,12,13,14,15,16,17,18]. Filipi et al. have examined the effect of VGT's on transient PM spikes [19], examined transient PM relative to quasi-static emissions [20] and made cycle resolved measurements of in-cylinder constituents during transients [21]. Rakopoulos et al. have examined the effect of engine parameters on transient emissions [22], effect of model simplifications on transient model predictions [23] and the effect of cold start and idle speed on turbocharger lag and transient emissions [24]. Nuszowski et al. have studied the effect of throttle control on cumulative cycle PM production [25] and examined the usefulness of transient heat

release data [26]. Galindo et al. have characterized transient diesel combustion [27], examined the effect of exhaust manifold design [28] and valve overlap [29] on transient emissions. Reifarth et al. [30] have examined the effect of EGR routing design on transient air-handling. Darlington et al. [31] have successfully reduced transient smoke spikes by implementing transient air-fuel ratio restrictions. Many researchers have examined simplified air-handling models have been proposed for control of transient emissions [32,33,34,35,36,37].

PN research, transient or steady state, is a relatively new area of research and hence investigators [38,39,40,41,42,43,44,45,46,47,48] have primarily focused their efforts at measuring transient particle size distributions, characterizing it, and studying sensitivities. Liu et al. [38,39,40] have shown how transient engine parameters affect both size and concentration of emitted particles and how these are different from corresponding steady state emissions. Kass et al. [41], Pagan [42] and Bertola et al. [43] have studied the effect of engine parameters including injection pressure on particle number concentration and their results are directly relevant to the current work. Also relevant are the findings of Desantes et al. [44] who have studied the effect of post injection on particle size distribution. Other researchers [46,47,48] have studied the effect of pilot injection, EGR fraction and fuel properties on size distribution. Such studies are also increasingly being performed by SI engine researchers [49], and are expected to increase as direct injected SI with turbocharging gains popularity.

It is well known to experienced calibration engineers that lack of in-cylinder Oxygen easily surpasses any other engine parameter as the primary cause of transient PM spikes during the turbocharger lag period. Yet transient PM spikes cannot be easily detected by the ECM estimated fuel-Oxygen ratio and cannot be controlled by a single fuel-Oxygen ratio limit, which is why it is common practice to use speed-load based tables of fuel-Oxygen limits. The author has recently investigated this phenomenon [50] as also the baffling lack of generalization characteristic of empirical PM models [50,11,12,13]. It was noticed that many kinds of empirical models could 'fit' the data but model predictions for test data generated from any transient calibration significantly different than the one used to generate training data was poor. The primary issue hindering model generality was determined to be lack of accurate in-cylinder Oxygen estimates. The models relied on ECM estimates of charge flow and EGR fraction to calculate in-cylinder Oxygen mass. It was shown that ECM correlations for volumetric efficiency built with steady state data were rendered inaccurate during the turbocharger lag period because of high exhaust to intake manifold pressure ratios that are typical of such events but unachievable at steady state. Since transient charge flow cannot be measured directly there is no alternative to an (inaccurate) ECM estimate. However such estimates could be 'corrected' for by mining the data for the effects of manifold

pressure ratio on volumetric efficiency at different engine speeds and EGR fractions. It was observed that these variables when coupled with the ECM based fuel-Oxygen ratio, had sufficient information content to detect PM spikes in real time. Decision trees are ideally suited to such tasks. A decision tree was therefore used to predict transient opacity spikes (large spikes are primarily the result of fuel-Oxygen ratio) based on not only the ECM based estimated fuel-Oxygen ratio but also the manifold pressure ratio, engine speed and EGR fraction. The results were surprisingly accurate as well as robust, e.g. the decision tree discussed shortly was trained on transient snap throttle data but could predict about 94% of all PM spikes occurring during the turbocharger lag period of the FTP cycle. Classification type decision trees that can derive 'rules' that relate predictor variables to one or more classification of the response variable are commonly used in data mining. A discussion on decision trees is beyond the scope of the current work; they are commonly discussed in data mining texts, e.g. [51].

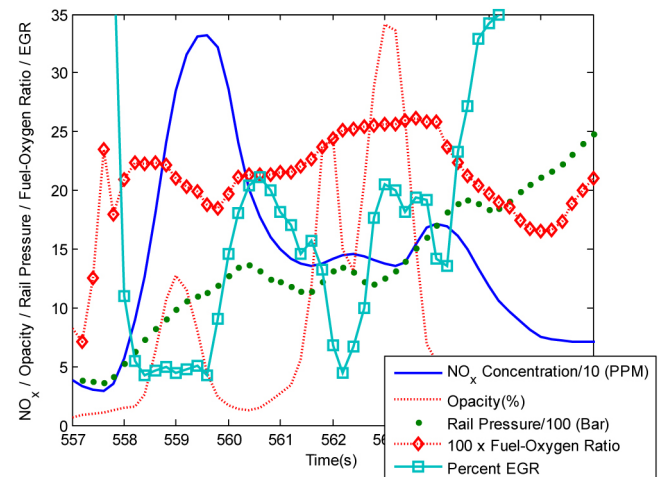


**Figure 1. The representative transient segment examined throughout the current work demonstrates how narrow the typical turbocharger lag PM/opacity spike is relative to the encompassing NO<sub>x</sub> spike thus rendering targeted PM reduction feasible**

Given the ability to predict PM spikes in real time using decision trees, a multitude of opportunities to reduce transient PM and PN emerge and the current work addresses two of them, targeted injection pressure and post injection. Figure 1 shows a transient segment containing the largest opacity spike (the 95<sup>th</sup> percentile opacity over the cycle was 5%) and second largest NO<sub>x</sub> spike (95<sup>th</sup> percentile NO<sub>x</sub> concentration over the cycle was 133 PPM) in the FTP cycle run with the default engine calibration. This segment has been examined throughout the current work and is representative of the turbocharger lag period of the current engine as well as other engines data investigated by the author [11-12]. Anything exceeding 95<sup>th</sup> percentile over the FTP cycle has been classified as a spike. The opacity/PM spikes are a result of

high fuel-air or fuel-Oxygen ratios resulting from low boost pressures while the turbocharger is gaining speed. The  $\text{NO}_x$  concentration spikes are a result of EGR deficits; the EGR valve is typically partially or completely closed during the turbocharger lag period in order to increase the turbocharger speed rapidly. It can be seen that opacity spike is much narrower than the encompassing  $\text{NO}_x$  spike. If injection pressure were to be suddenly raised at only the high opacity points, it could reduce PM without a significant  $\text{NO}_x$  penalty because of narrowness of the opacity spike. The typical air-fuel ratio during an opacity spike is near-stoichiometric (see [figure 13](#)), hence the sensitivity of  $\text{NO}_x$  to high injection pressure is expected to be lower than usual. Another possibility would be to include a targeted post injection optimized for near-stoichiometric air-fuel ratios at the high opacity points. Both these strategies have been explored with dimensional and empirical modeling in this work, since access to modify the engine control strategy was not available and experimental verification was therefore impossible. Two additional observations from [figure 1](#) are of value. First, it should be noted how the (ECM estimated) fuel-Oxygen ratio is not entirely consistent with the opacity spikes; these inconsistencies are largely explained by manifold pressure ratio. Secondly the rail pressure seems to be increasing throughout; this is because higher speeds and loads require higher rail pressure to manage ignition delay and maintain optimum diffusion burn rates. In practice the rail pressure ECM tables are tuned to meet emissions with minimum fuel consumption and this generally results in lower rail pressures at low engine speeds and loads. Since the turbocharger lag corresponds to a period of transition from lower to higher speeds and loads, the rail pressures are typically low, and in terms of PM, this makes a bad situation worse. Optimal engine parameters during transient operation cannot be solely functions of speed and load. Some engine controllers have separate ECM tables for transients and some use transient modifiers that for example would increase rail pressure or adjust injection timing based on rate of change of engine speed. Such modifiers typically increase  $\text{NO}_x$  significantly because they apply over the entire transient, in addition they are hard to design and often have unintended consequences. The targeted model based approach presented in this work incurs lower  $\text{NO}_x$  penalties relative to such blanket approaches such as separate transient tables and transient modifiers. Based on the results of previously mentioned PN researchers Kass et al. [41], Pagan [42], Bertola et al. [43] and Desantes et al. [44], it is believed that both strategies explored in this work lower PN in addition to PM, though it is felt that additional work is required to characterize the effect of injection pressure and post injection on *transient* size distribution during the turbocharger lag period.

A commercially available 2009 heavy duty production diesel engine equipped with an electronically controlled common rail fuel system, high pressure EGR system and variable geometry turbocharger was run in a standard engine

test cell facility for this work. Steady state charge flow rates were calculated from fresh air flow measurements made upstream of the engine and intake manifold  $\text{CO}_2$  measurements (to estimate EGR fraction). During transient operation the in-cylinder charge flow and volumetric efficiency estimates made by the ECM could be recorded with the test cell measurements, and were synchronized to correspond to identical timestamps. The particular correlations for volumetric efficiency used by the ECM were not available to the author, but the ECM estimates for volumetric efficiency could be derived from the ECM charge flow and EGR fraction estimates. The engine produced about 0.5 g/hp-hr BS $\text{NO}_x$  over the heavy duty FTP cycle, which was repeated to measure the repeatability of opacity (0.5%) and PM measurements (3% cycle cumulative). The engine was also run at steady state conditions to generate data for calibrating the dimensional (GT-Power) model. Snap throttle cycles comprising of opening the throttle instantaneously from 0-100% at different engine speeds were run in order to generate a broad multidimensional dataset to train empirical emission models according to previous recommendations made by the author [11] for this purpose.

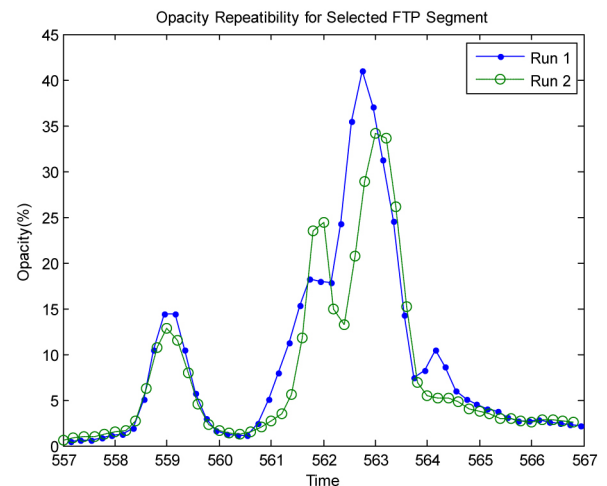


**Figure 2. Repeat opacity measurements over the transient segment examined in this work. The average deviation over the entire FTP cycle was 0.5% opacity and the measured cumulative PM mass was repeatable within 3%**

The following discussion is broadly divided into three broad sections. The first section describes how decision trees can detect opacity spikes exceeding 5% opacity during the turbocharger lag period in real time. The second section describes the PM reduction possible with targeted injection strategies. The consequences of adjustment of rail pressure and post injection at high opacity/PM points have been explored with GT-Power, since it was not possible to implement those strategies on the engine. Only the transient segment shown in [figure 2](#) has been examined however, because of the computational effort involved in replicating

transient conditions exactly (at the 50 data points collected over the 10s segment), as will be explained shortly. Though this segment is representative it does not provide the emission tradeoff over the entire FTP cycle. For that purpose empirical models have been built and used according to the guidelines specified in previous work [11-12]. The third section describes the emission tradeoff resulting from adjusting rail pressure at high opacity points, predicted by such empirical models (adjustment to the post injection strategy could not be explored empirically because of model reliability considerations). The benefits of the targeted strategy were explored at different engine-out  $\text{NO}_x$  levels. Model input for engine-out  $\text{BSNO}_x$  levels other than 0.5 g/hp-hr (which were measured or ECM estimated), came from optimizing transient tables at each level with the aid of the model based transient calibration process developed previously [11-12].

## PM SPIKE DETECTION

This section describes the difficulty of predicting PM spikes and the proposed decision tree solution in two separate sections.

### THE DIFFCULTY OF PREDICTING PM SPIKES

Transient PM is commonly known to be difficult to predict, empirically or otherwise, owing to the complex nature of PM formation and measurement uncertainty. Transient spikes can be often correlated to fuel-Oxygen ratio but empirical models using such correlations cannot capture spike events satisfactorily and are calibration dependent, though they can be used to predict cumulative cycle PM within 10% error [12-13]. Figure 3 explains why. It shows all the measured snap throttle cycle data used for building the decision trees in the current work over the opacity and ECM estimated fuel-oxygen ratio space. Although opacity depends on many factors it is commonly known from steady state data that opacities greater than approximately 5% are caused by fresh air flow deficits and are largely a function of fuel-Oxygen ratio. Yet it is seen from figure 3 that between fuel-Oxygen ratios of 0.2-0.3 (which roughly corresponds to air-fuel ratios ranging from 21.5 to 14.3 without EGR) opacities greater than 5% are distributed normally with a peak near 0.23, whereas a near-monotonic increase of opacity with fuel-Oxygen ratio is expected. Further there exist numerous near zero opacity or low opacity measurements at high near-stoichiometric fuel-Oxygen ratios. There are two primary reasons for this noise, measurement delay and inaccuracies in estimating the fuel-Oxygen ratio, both of which are inevitable. Figure 4 demonstrates the rapid change in the fuel-oxygen ratio and the relatively gradual change in measured opacity. The delay is the combined result of transport delay, manifold and plumbing volume capacitance and the filtering used on the raw signal. All opacity data used in this work including that shown in figure 3 has been adjusted by a constant delay that best explains the data and is determined

empirically [11], yet the discrepancy between the ECM estimated fuel-Oxygen ratio and measured opacity at the boundaries of a spike, e.g. between 317-318s in figure cannot be addressed by a constant delay and cannot be detected in real time. Further the ECM estimate of the fuel-Oxygen ratio shown in figures 3 and 4 is inaccurate during the turbocharger lag period [11,50] because the large manifold pressure ratio during such events that causes the volumetric efficiency to be overpredicted and the EGR fraction to be underpredicted thus rendering the fuel-Oxygen ratio to be underpredicted. The fundamental reason is that ECM correlations for volumetric efficiency and EGR fractions are calibrated with steady state data which experience much lower engine pressure ratios than corresponding transient data at similar operating conditions. Detailed evidence of the inaccuracy of ECM correlations calibrated with steady state data is presented available in related work [50].

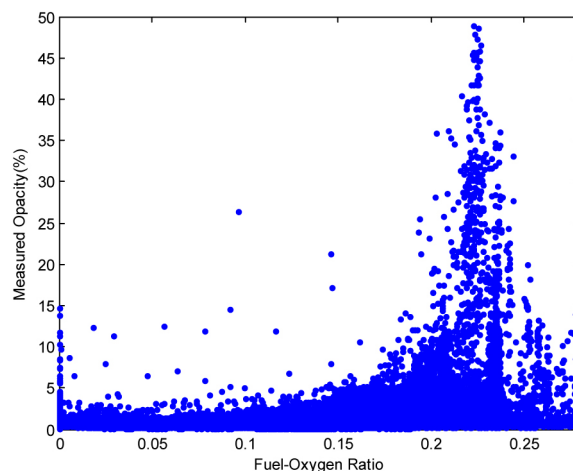


**Figure 3. Measured Opacity against ECM estimated fuel-Oxygen ratios from the snap throttle data used to build decision trees**

On the other hand the manifold pressure ratio (not an engine parameter) in conjunction with ECM estimated fuel-Oxygen ratio and EGR fraction was observed to be sufficient information to enable detection of opacity spikes in real time. Decision trees have been used to process this information and correlate instantaneous engine pressure ratio and ECM estimates to opacity.

### PM SPIKE DETECTION WITH DECISION TREES

The training data used to build the decision trees came from 4 snap throttle cycles each of which was run with a different engine calibration. According to the author's recommendations for generating transient training data that result in calibration independent empirical models [11], transient cycles should be run with different calibrations till the correlations between engine parameters in the training data cease to decrease. In practice as many snap throttle cycle cycles with different transient calibrations were run as

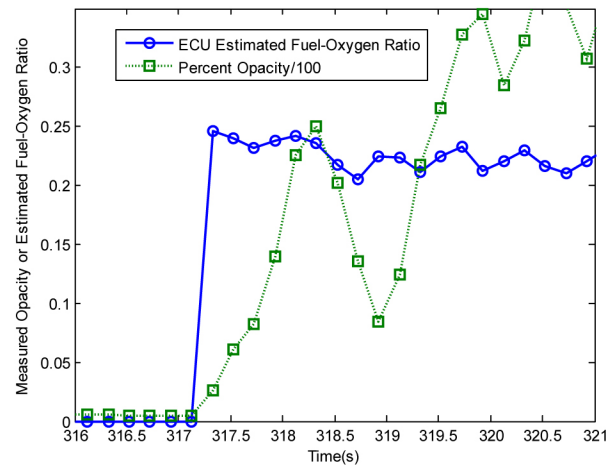


Figure 4. A delay in the measured opacity is evident between 317 and 318s even though the data has been adjusted for an optimal but constant phase shift (0.7s). Such delays cannot be accounted for in real time.

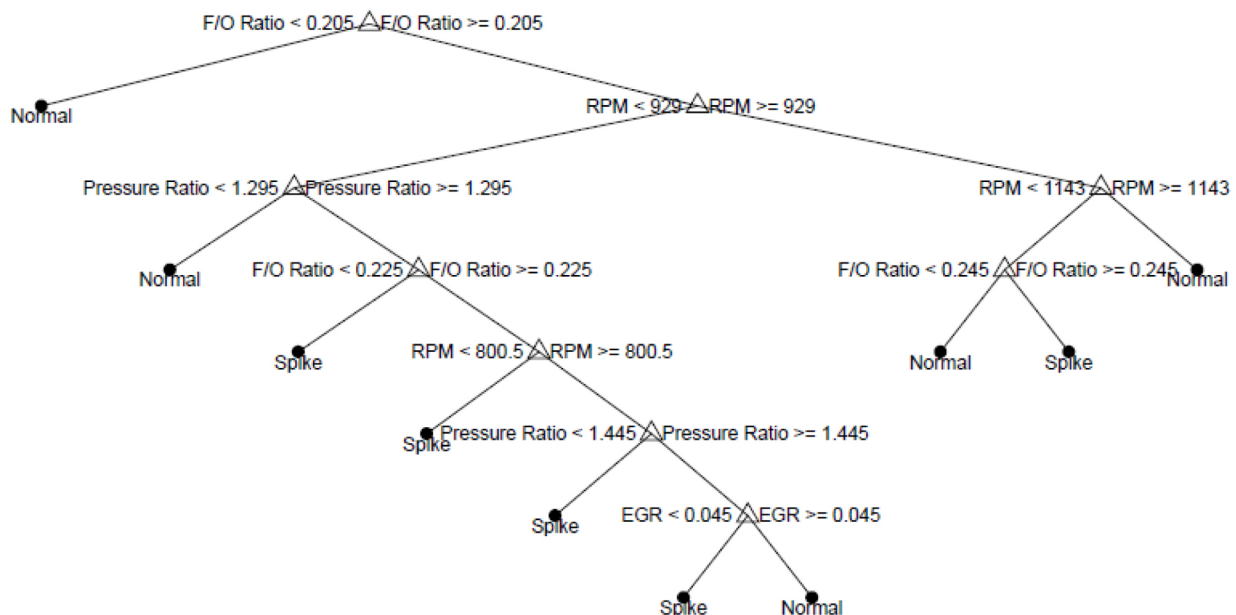


Figure 5. Classification type decision tree built in MATLAB to classify the opacity at each data point as either a 'spike' or 'normal'

allowed by the limited time available for engine testing. Then an algorithm was run to combinatorially select the subset of snap throttle cycles resulting in the lowest sum of correlations among its parameters. 4 snap throttle cycles were chosen from about 40 transient cycles including FTP cycles by running the algorithm through 1500 iterations during each of which all transient cycles were examined in random order and added to the training dataset only if they decreased the sum of correlations. The resulting decision tree is shown by figure 5. This classification type decision tree was built in MATLAB. Data points with opacities exceeding the 95<sup>th</sup> percentile (5%) were classified as 'spikes' while all other points were classified as 'normal' in the training data. Only

data with RPM lower than 1250 RPM was eligible to be classified as spikes, a small number of spikes were observed at higher engine speeds (classified as 'Mode B' spikes [11,12,51]) but they did not correspond to the turbocharger lag period. The fuel-Oxygen ratio believed to be the primary predictor of PM spikes is estimated with varying degree of inaccuracy by the ECM at different engine speeds, EGR fractions and manifold pressure ratios all of which affect the volumetric efficiency overestimation and EGR fraction underestimation described above. These four variables were therefore chosen as predictors for the decision tree. The split criteria used to select each node was the default Gini's diversity index; the predictor and its value that maximizes the