

Beneficial and problematic interactions between NO_x trapping materials and carbonaceous particulate matter.

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Abstract

The presence of a NO_x trapping BaO component with a Pt active phase does not *per-se* promote carbon combustion. However when coupled with trap regeneration promotion of soot combustion is seen. Operating NO_x trapping materials promote combustion due to the periodic localised increases in [NO₂]_(g) generated during the regeneration rather than due to a co-generated exotherm. However, it has been noted that the presence of soot prevents NO_x traps from employing their full trapping capacity.

Keywords: Particulate combustion, NO_x trap promotion, transient studies.

Introduction

Carbonaceous Particulate Matter (PM) forms around sulphur nucleation sites within combustion chambers of diesel engines and has several well documented adverse affects both on human health and the urban and global environment [1-3]. One method for the removal of such particulates from exhaust streams involves trapping them within cordierite monolith filters and subsequently oxidising them to CO₂ [4]. During this process either O₂ or NO/O₂ mixtures can be used as oxidants [5]. The presence of NO improves the rate of combustion and the mechanism of this promotion involves the transfer of an oxygen atom to soot particles *via* an NO_{2(g)} intermediate [6], Scheme 1.

Another after-treatment system used in the purification of diesel or lean-burn gasoline engines is a NO_x trap. This removes NO from a fuel-lean exhaust stream by converting NO_(g) into Ba(NO₃)_{2(s)} through reaction with O₂ and BaO. The first step in this conversion is the oxidation of NO into NO₂, *i.e.* the same step that operates in the NO promotion of soot combustion detailed above. Once the trap becomes saturated it is regenerated by a pulse of hydrocarbons and the NO_x released and reduced on a Rh

component [7]. A simplified scheme of NO_x storage and reduction is shown in Scheme 2.

The combination of these two features in the after-treatment system of a diesel engine would be a major advancement in the development of 4-way catalysts [8-10], *i.e.* a single bed catalysing the removal of CO, Volatile Organic Compounds (VOC), NO_x and PM from the exhaust of fuel efficient diesel vehicles (the Toyota DPNR concept).

There have been relatively few reports [11-14] of materials that can both store NO_x for and NSR cycle and also combust soot using an NO₂ promoter. This is unusual given that the same first step operates in both cycles and materials that have activity in one cycle might be expected to show some activity in the second. Significantly, there have been recent reports [11, 15, 16, 18] that the combustion of PM from diesel exhausts can be improved through the incorporation of a NO_x trapping component within the filter.

Also there are relatively few reports regarding any detrimental interactions between NO_x traps and soot combustion catalysts although Makkee *et al.* [14] have reported that the NO_x storage capacity of NSR materials decreases upon aging under soot oxidising conditions.

In this work we have evaluated the effect of the presence of a NO_x trapping component (BaO) upon the activity of model 0.3% Pt/SiO₂ catalysts for promoting the combustion of soot. We also analyse for any effects that the presence of soot has upon the behaviour of the NO_x trap in terms of NO_x trapping capacity.

Experimental

Catalyst Preparation

The model catalysts studied, 0.3% Pt/SiO₂ and 0.3%Pt/5%Ba/SiO₂, were prepared using standard wet impregnation techniques from solutions of H₂Pt(OH)₆ (dissolved in dilute HNO₃) and Ba(C₂H₃O₂)₂ dissolved in water. The SiO₂ was provided by Grace and had a surface area of 256 m²g⁻¹. SiO₂ rather than the more conventional Al₂O₃ was chosen as a support due to the fact that it does not interact with or store NO_x and this makes de-convolution of the transient experiments (see later) more straightforward.

Accurately weighed samples of $\text{H}_2\text{Pt}(\text{OH})_6$ sufficient to yield a nominal Pt loading of 0.3% were dissolved in ~1ml (sufficient to fill the pores of the support material) of 0.5M HNO_3 and the solution was added dropwise to 1g of SiO_2 . The mixture was then dried overnight at 110 °C and calcined in air for 2h at 500 °C.

Similarly accurately weighed samples of $\text{Ba}(\text{C}_2\text{H}_3\text{O}_2)_2$, sufficient to yield a Ba loading of 5% Ba, were dissolved in 1 ml of water and the solution was again added dropwise to 1g of SiO_2 . This mixture was then dried and calcined as before.

In the ternary catalyst (Pt/Ba/ SiO_2) the SiO_2 was firstly impregnated with Ba, dried and calcined before subsequently being impregnated with Pt (again followed by drying and calcination steps) in order to maximise the exposure of the Pt which is the active component in the $\text{NO} \rightarrow \text{NO}_2$ transformation.

Activity Measurements

Activity in the soot combustion reaction was studied by holding the catalyst/soot mixtures (Degussa Printex L) with quartz wool in a reactor tube connected to a gas manifold and an online GC (Shimadzu FID GC 8A fitted with a methanator) or mass spectrometer (Prolab). The catalysts were mixed with soot in a 1 part catalyst:2 part soot ratio. A mixture of catalyst (212-350 μm) and soot was mixed thoroughly using a spatula (approximating a “loose contact” situation) and subsequently this mixture was wet into a paste using the minimum amount of CH_3OH . The paste was then dried (to remove methanol) and the resultant solid sieved to particle sizes of (212-350 μm). This treatment provides some adhesion between the catalyst particles and the carbon.

The combustion of soot in the mixtures was studied under *pseudo*-steady state conditions, *i.e.* in a flow of O_2 (4%) or O_2 (3.4%) and NO (1320 ppm) in N_2 at several temperatures and under transient conditions, *i.e.* at 400 °C in a flow of He with periodic injection of various combinations of NO, O_2 and H_2 through the manipulation of electrically actuated 4-way valves. It should be noted that during the transient studies when a gas is switched into the reactant stream an equivalent volume of He is removed thus keeping the overall flow constant.

Temperature Programmed Desorption

A fresh sample of Pt/Ba/SiO₂ was exposed (at 400 °C) to NO (1250 ppm) and O₂ (4.5 %) mixture for 60 s in the presence and absence of soot. In both cases the same mass of catalyst was used so direct comparison of the profiles generated is possible. The catalyst (or catalyst/soot mixture) was then cooled to 300 °C and subsequently ramped in a flow of He to 650 °C at a ramp rate of 20 °C min⁻¹. The exit gases were continuously monitored using on line mass spectrometry.

Results and Discussion

Pseudo steady-state reactions

Figure 1 shows the *pseudo* steady-state activities of the Pt/SiO₂ and Pt/Ba/SiO₂ catalysts as a function of temperature in the presence and absence of NO. Obviously more combustion takes place in all cases at higher temperatures but it can also be clearly seen that over both catalysts the production of CO₂ is enhanced in the presence of NO due to the operation of the mechanism shown in Scheme 1.

Control experiments in the presence and absence of NO either using SiO₂ support material or Ba/SiO₂ as a catalyst show lower activities than these catalysts in the combustion in O₂ and there is no effect on activity seen following the addition of NO – showing the necessity of an NO oxidation functionality for promotion.

What is also noticeable is that there is no discernable difference in activity between the Pt/SiO₂ catalyst and the Pt/Ba/SiO₂ material, *i.e.* there is **no** promotional effect seen once a NO_x trap is incorporated into the catalytic mixture. If anything, the presence of Ba slightly poisons the reaction when NO is in the feed. Therefore the presence of a NO_x trapping component coupled with a Pt active phase does not promote steady state soot combustion. We have previously noted similar results over BaO combined with less active (regarding the promotion of the NO→NO₂ reaction) FeZSM-5 catalysts [17].

Suzuki *et al.* [11] have noted increased combustion of PM following the incorporation of a NO_x trap into the catalytic material. However, their experiments involved transient Temperature Programmed Reaction monitoring of the production of CO₂. These measurements are obviously not steady-state or *pseudo* steady-state in nature. They

ascribe this increased activity to direct contact between the soot particles and the nitrated NO_x storage material. Following the results obtained above, where nitrated NO_x storage material behaves in exactly the same manner as catalysts without such sites, we suggest rather, that Suzuki's results are due to desorption of NO_2 from the NO_x storage sites as the temperature is raised and the subsequent use of this NO_2 to either combust $\text{C}_{(s)}$ or activate it for combustion with O_2 . Such processes cannot take place in the absence of the NO_x storage component and hence promotion is seen in the presence of NO_x traps.

Transient Studies

However, it should be recalled that once operational NO_x traps do not work under steady-state or *pseudo*-steady state conditions (see Scheme 2). For 99% of the time the NO_x storage and reduction catalyst exists under a flow containing (as reactive species) mostly O_2 and NO (as the flow in which the *pseudo*-steady state measurements were taken above). Once the BaO NO_x trap is saturated, it is regenerated using a rich pulse of hydrocarbons. The material exists in this mixture $\sim 1\%$ of the time (Scheme 2). These hydrocarbons regenerate the BaO trapping material, cause the release of $\text{NO}_{2(g)}$ and reduce the Rh component of a catalyst to the metal (upon which NO_x is subsequently reduced) while concomitantly themselves oxidising to CO_2 and H_2O .

It has also been reported that that an alternatively lean and rich operation promotes soot oxidation to a greater extent than a constant lean atmosphere [18]. Suzuki and Matsumoto [11] ascribe this to a second mechanism of promotion (as well their "contact" mechanism discussed above) and discuss this mechanism in terms of "activated species decomposed under the rich atmosphere" oxidising PM.

There are two features of this rich pulse that could be envisaged to promote PM combustion, *i.e.* (a) the localised exotherm caused when the hydrocarbons combust and (b) the transient localised increase in $[\text{NO}_2]_{(g)}$. In their article [11] Suzuki and Matsumoto neglected to account for the possibility of the former effect causing promotion of soot combustion.

In order to determine which of these two potentially promotional mechanisms is the more important in promoting combustion over the NO_x trapping materials we have

attempted to mimic these *effects* of NO_x trap regeneration (exotherm and NO₂ increase) over a Pt/SiO₂/soot mixture in a flow of NO/O₂ at 400 °C using pulses of different gas mixtures.

Firstly, pulses of H₂ (which immediately combusts at this temperature) were added to mimic the exotherm generated when hydrocarbons interact with Pt/Ba(NO₃)₂ in the presence of O₂ and secondly, pulses of NO were added mimic the latter effect, *i.e.* transiently increased concentrations of [NO₂]_(g). In both cases before the experiment was begun the samples were subjected to periodic treatments in O₂ and NO/O₂ in order to remove any heterogeneous carbon from the system.

Figure 2 shows the CO₂ profiles formed during these transient experiments. It should be noted that control experiments performed over the SiO₂ support materials and Ba/SiO₂ catalysts show that their soot combustion activities remain relatively unaffected by either pulses of H₂ or NO.

At the beginning of the experiment the mixture is held in a flow of He at 400 °C. After 1 minute NO (1100 ppm) and O₂ (4 %) are switched into the flow and soot combustion commences (as measured by on-line mass spectrometry). The system is left for a further minute and then the second gas (NO, increasing overall [NO] to 3060ppm or H₂, giving a [H₂]_{inlet} of 3000 ppm) is switched in for 10 seconds. The system is then left in a flow of NO/O₂ for 30 seconds. This pulse sequence is repeated a further 4 times before the NO/O₂ is finally switched out. For clarity in figure 2 only one point in 100 is labelled to distinguish the different profiles.

Figure 2 clearly shows that the addition of extra NO_x is a much more important feature in terms of promoting soot combustion than the exotherm generated when H₂ is combusted (measured to be of the order of 5 °C).

Interestingly when only O₂ is used as an oxidant the overall conversion to CO₂ is much lower (as expected since the promotional effect of NO is removed) but the effect of the H₂-generated exotherm is proportionately much greater. This is shown as the lower profile in figure 2.

The results presented above have shown that of the two mechanisms suggested by Suzuki and Matsumoto for the NO_x traps promotion of soot combustion (a) contact between a soot particle and nitrated NO_x trap and (b) the activated species decomposed under the rich atmosphere oxidising soot, that the latter is of far greater importance. We have also discounted a previously unconsidered possibility, *i.e.* that the exotherm caused by regeneration is the reason for the increase seen in soot combustion activity. This does not preclude the possibility that a larger exotherm caused by the combustion of higher concentrations of hydrocarbons would have a larger effect.

Effects of PM on NO_x storage capacities

Having ascertained the reason why NO_x traps promote the combustion of soot the final area of interest in this work was to evaluate whether the presence of soot in any way affects the *sorption capacity* of a NO_x trap. This feature directly affects the first step in the NO_x trap cycle, *i.e.* where NO is oxidised to NO₂ over Pt and subsequently the NO₂ adsorbs on, and reacts with, BaO. We studied this effect using a Temperature Programmed Desorption technique to analyse the concentrations of NO_x adsorbed on a fresh sample of Pt/Ba/SiO₂ following exposure (at 400 °C) to NO (1250 ppm) and O₂ (4.5 %) mixture for 60 s in the presence and absence of soot. The catalysts were then cooled to 300 °C and subsequently ramped in a flow of He to 650 °C at a ramp rate of 20 °C min⁻¹. Control experiments studying adsorption of NO_x onto (and desorption of NO_x from) SiO₂, Ba/SiO₂, Pt/SiO₂ and soot alone have shown that the adsorption onto each of these species is negligible under the conditions of the experiment.

Both materials show desorptions which are characteristic of the decomposition of Ba(NO₃)₂ [19] and, from figure 3, it is clear that the sample which had been dosed in the presence of soot desorbs (and thus initially adsorbs) far less NO_x than that which was dosed in the absence of soot (643 μmol g⁻¹ as against 205 μmol g⁻¹).

While the former concentration is relatively close to the theoretical limit for the formation of Ba(NO₃)₂ (the loading of Ba is 364 μmol g⁻¹ giving a maximum NO_x trapping capacity of 728 μmol g⁻¹) increases in the length of the dosing time shown (60s) have little effect on the latter NO_x loadings (results not shown).

As an aside, only very small amounts ($<10\ \mu\text{mol}$) of CO (confirmed as CO rather than N_2 by analysis of the $m/e = 12$ signal) were formed during the TPD. Therefore the possibility that equivalent amounts of NO_x were initially adsorbed onto the Pt/Ba/ SiO_2 material in the presence and absence of soot but that in the presence of soot desorbing NO_2 was reduced to N_2 and soot concomitantly oxidised can be discounted as the reason for seeing less desorbed NO_x . Less NO desorbed from the second material simply because initially less was adsorbed during the dose.

This result shows that the presence of soot decreases the sorption capacity of the NO_x trapping component. The obvious explanation for these observations is that in the presence of soot the NO_2 formed over the Pt component (a necessary prerequisite to the formation of $\text{Ba}(\text{NO}_3)_2$) reacts with soot before reacting with BaO (see Scheme 3).

This feature, *i.e.* the fact that the NO_x trapping component is less able to store NO_x in the presence of soot, has consequences for the engine management cycle required to most efficiently operate a NO_x trap (regarding frequency of regeneration or catalyst NO_x trap loadings required for efficient deNO_x) if amalgamating these two functions (NO_x removal and Particulate Matter combustion) is to be considered in so called 4-way catalysis.

There is a possible further consequence of the presence of soot on the NSR cycle which relates to the reduction step. The desorbed species in NSR (NO_2) is reduced over a Rh component and it has been widely reported that NO_2 is a more active oxidant (and thus easier to reduce) than NO [20, 21]. Therefore there is also an issue with the possibility of carbon reducing liberated NO_2 to NO before the reduction component of the NSR catalyst “sees” and fully reduces it to N_2 . If the particular reduction process relies on a concentration of NO_2 rather than of NO (which can be the case in lean- NO_x reduction with hydrocarbons [20] or NH_3 [21]) then this might also decrease the effectiveness of the NSR cycle. Further work is ongoing to determine whether this is the case.

Conclusions

We have found that the reason that BaO promotes particulate combustion is related to the transient release of NO_2 during trap regeneration. The exotherm generated during

the regeneration plays a more minor role in the promotion (although it is more significant in the absence of NO). On the other hand the activity of nitrated BaO in promoting soot combustion is negligible. The presence of soot, on the other hand, is detrimental to the performance of a NO_x trap since it offers another reaction route for the utilisation of NO₂ rather than the desired formation of Ba(NO₃)₂.

Acknowledgements

We gratefully acknowledge the Environmental Protection Agency (Ireland) (EPA) for funding this research.

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Figure 1

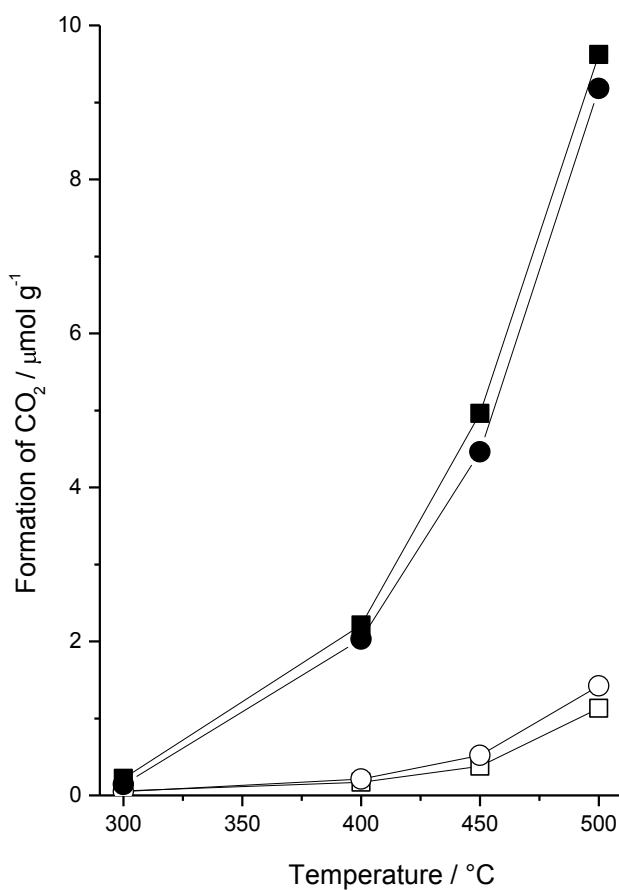


Figure 1: *Pseudo* Steady-State soot combustion activity of Pt/SiO₂ (□,■) and Pt/Ba/SiO₂ (○,●) catalysts using air (open symbols) and NO/air (filled symbols) as oxidants.

Figure 2

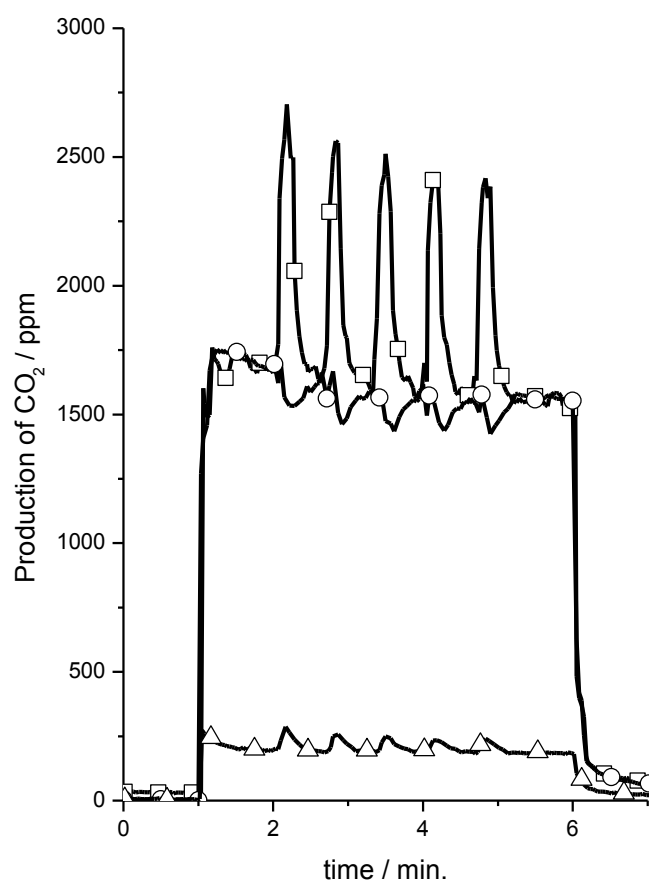


Figure 2: Transient production of CO₂ from a 0.3%Pt/SiO₂ catalyst/soot mixture in a flow of NO + O₂ with periodic injection of NO (□) and H₂ (○). The lower profile (△) shows the effect of injecting H₂ into a stream of O₂ over the catalyst/soot mixture.

Figure 3

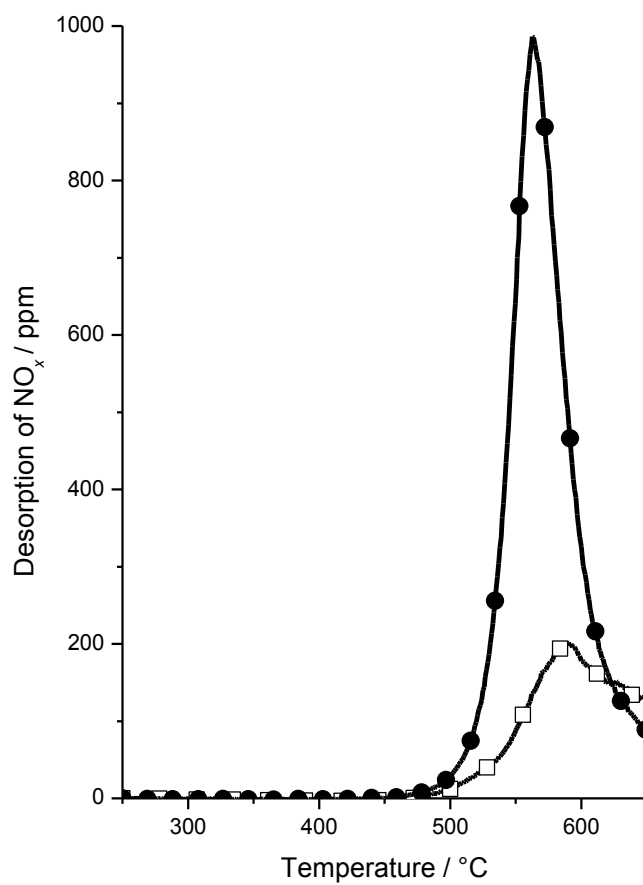
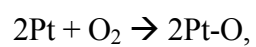
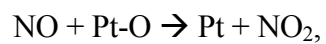


Figure 3: TPD of NO from Pt/Ba/SiO₂ dosed with equivalent concentrations of NO/O₂ at 400 °C in the presence of soot (□) and in the absence of soot (•).

Scheme 1



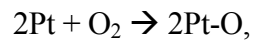
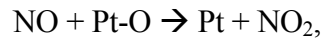
followed by



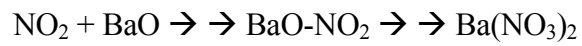
Scheme 1: A simplified mechanism showing NO promotion of soot combustion.

Scheme 2

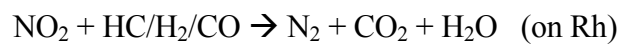
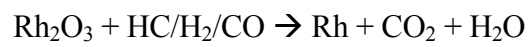
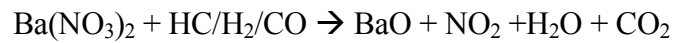
NO_x Storage (99% of time)



followed by

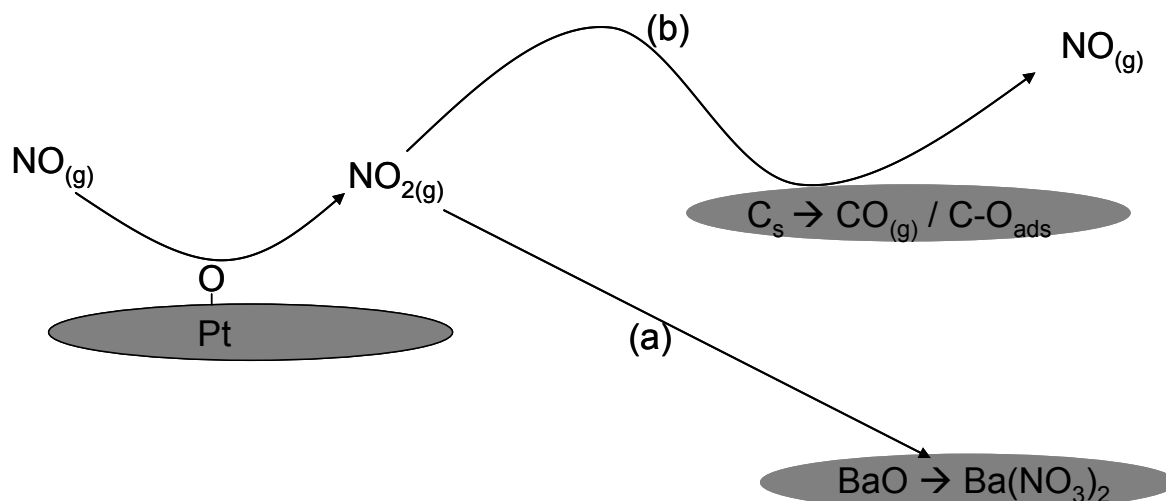


NO_x Reduction (1% of time)



Scheme 2: A simplified mechanism showing NO_x storage and reduction

Scheme 3



Scheme 3: The proposed mechanism by which Particulate Matter decreases the NO_x adsorption capacity of a NO_x trap. NO_2 formed over oxidised Pt can either adsorb on BaO (eventually forming $\text{Ba}(\text{NO}_3)_2$) (route a) or, in the presence of PM, interact with carbon and become reduced to NO (route b). The latter route then precludes the formation of $\text{Ba}(\text{NO}_3)_2$.