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STUDY OF COSTS AND IMPACT UPON CO_2 AND PRIMARY NO_2 EMISSIONS OF A RANGE OF LIMITS FOR EMISSIONS OF NO_X AND PM IN THE TIMESCALE 2014

RD.08/337301.7

18 July 2008 **Client Confidential**

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1 INTRODUCTION

The DfT has requested Ricardo to perform a study relating to the impact of future aftertreatment technologies on NO_2 and CO_2 emissions. This report is in reply to the request.

2 OBJECTIVES

- To understand the impact of Heavy Duty future emissions control technologies on system cost, NO_2 and CO_2 emissions
- To understand the impact of future emissions control technologies on the environment and economy

3 LITERATURE REVIEW ON THE IMPACT OF FUTURE EMISSIONS CONTROL TECHNOLOGIES ON UNREGULATED EMISSIONS FOR HEAVY DUTY APPLICATIONS

This literature review will focus on nitrogen based unregulated emissions (NH_3, N_2O and NO_2) which are formed as a function of potential heavy duty aftertreatment. The aftertreatment technologies under discussion are oxidation catalysts (DOC), urea based selective catalytic reduction (SCR), lean NOx traps (LNT) and particulate filters (DPF).

3.1 N_2O Emissions

Using SCR technology, there are two potential mechanisms for N_2O formation, the reaction of NOx with NH_3 and oxidation of NH_3 slip over the clean up catalyst.

Under low temperature operation N_2O is formed via the decomposition of ammonium nitrate over the SCR catalyst. Figure 3-1: N_2O formation as a function of temperature shows the formation of N_2O as a function of temperature [1].

$$4NH_3 + 4NO_2 \rightarrow 2\ NH_4NO_3 + 2N_2 + 2H_2O \rightarrow 2N_2O + 2N_2 + 6H_2O$$

The nature of the SCR catalyst impacts N_2O formation[2]. Figure 3-2 shows how mixed oxide type catalyst show a strong selectivity to N_2O formation under high temperatures, whereas, the zeolite based catalysts have a much lower selectivity (ZSM5 is a specific type of zeolite which can be ion exchanged with metals such as copper or iron to alter the properties of the catalyst). Future emissions control technology, which has the requirement for a DPF will use zeolite based technology and will move away from the current use of mixed oxide catalysts. This is due to vanadium becoming volatile under high temperatures, which could occur during DPF regeneration. Currently vanadia based catalysts are not permitted in the US or Japan.

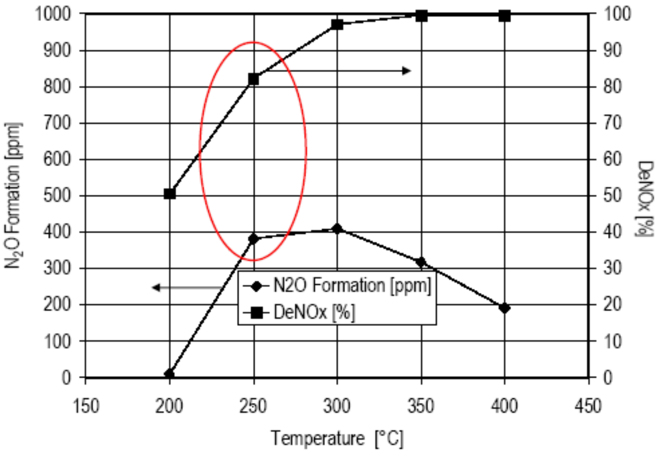

Figure 3-1: N_2O formation as a function of temperature

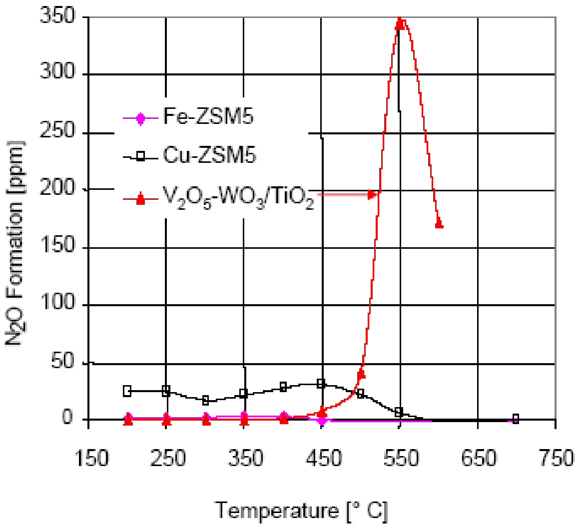

Figure 3-2: N_2O formation as a function of temperature for different SCR catalyst technologies

During SCR operation NH_3 slip can occur. The slip of ammonia is controlled by using an oxidising catalyst. There are 3 reactions, which could occur[3] and depending on the catalyst local environment, N_2O can be formed.

$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$
$2NH_3 + 3O_2 \rightarrow NO + NO_2 + 3H_2O$
$2NH_3 + 2O_2 \rightarrow N_2O + 3H_2O$

Figure 3-3, shows Ricardo data [4] from a Euro VI type application, which utilised a DPF system followed by an SCR system. Over the ETC, the engine out N_2O

emissions was zero. However, a limited amount of N_2O was formed over the DPF and this increased over the SCR system.

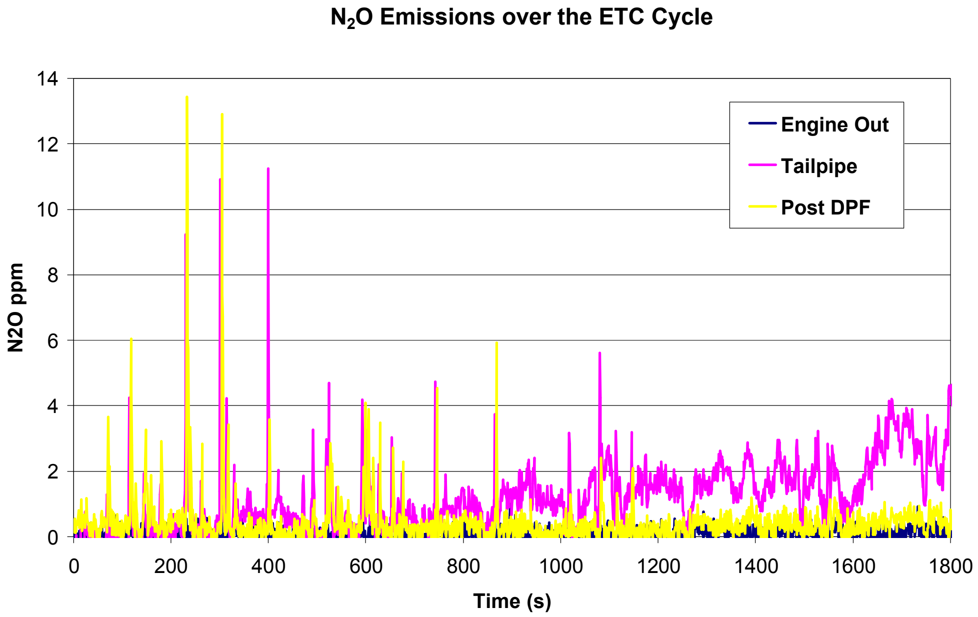

Figure 3-3: N_2O emissions during ETC cycle for a Euro 6 type application

Using LNT technology, N_2O emissions occur during a rich event [5], which is required for NOx control. Figure 3-4, shows the formation of N_2O and NH_3 during a rich event. N_2O is formed through partial reduction of NOx, whereas, NH_3 is formed through total reduction of NOx. Potentially in HD applications, the LNT may be followed by a coated DPF, which with sufficient oxygen could oxidise both N_2O and NH_3.

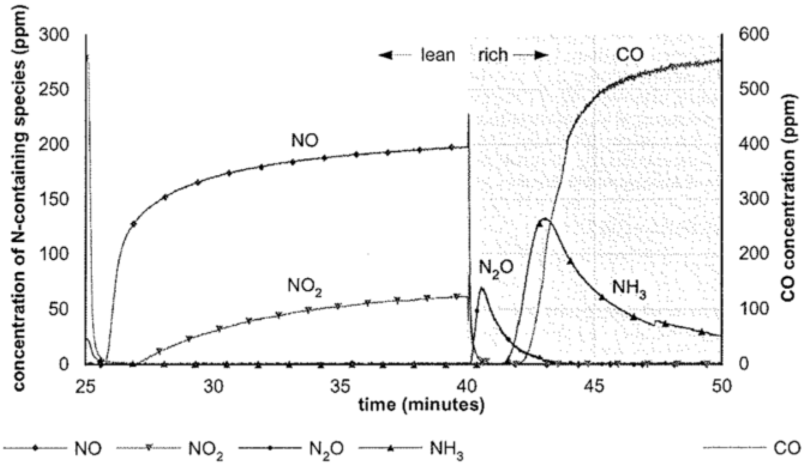

Figure 3-4: N_2O formation during LNT rich event

From a Ricardo HD LNT project [6], N_2O emissions were measured during rich events over the US FTP transient cycle. In this application, the N_2O emissions were not oxidised over the downstream DOC. Figure 3-5, shows peak N_2O emissions up to ~60 ppm.

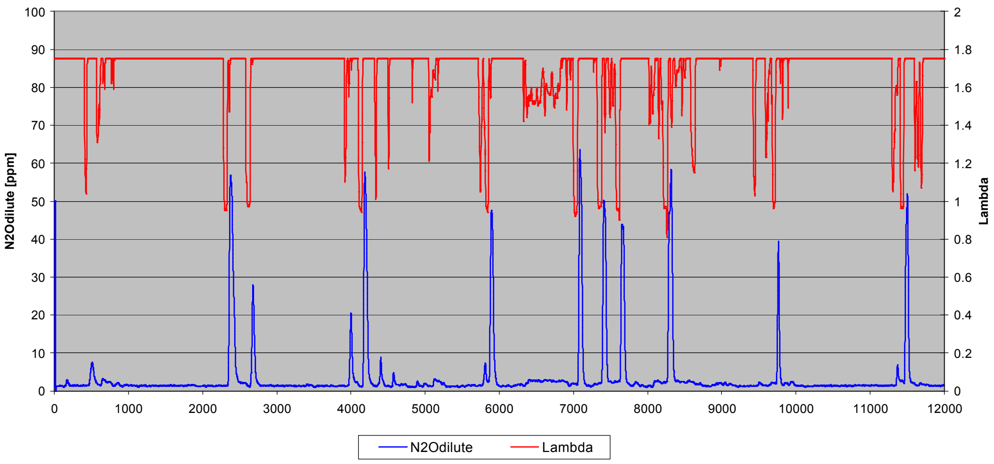

Figure 3-5: Ricardo HD FTP data shows N_2O emissions during rich events

3.2 NH_3 Emissions

NH_3 emissions from SCR applications are a function of ammonia stored on the catalyst, urea injection quantity and system temperature. The NH_3 slip is a function of the calibration. Figure 3-6, shows the NH_3 storage on the SCR catalyst as a function of temperature. Figure 3-7 and Figure 3-8 show the impact of different cycles on tailpipe NH_3 emissions[7]. Both tests used a clean up oxidation catalyst, which led to low tailpipe levels.

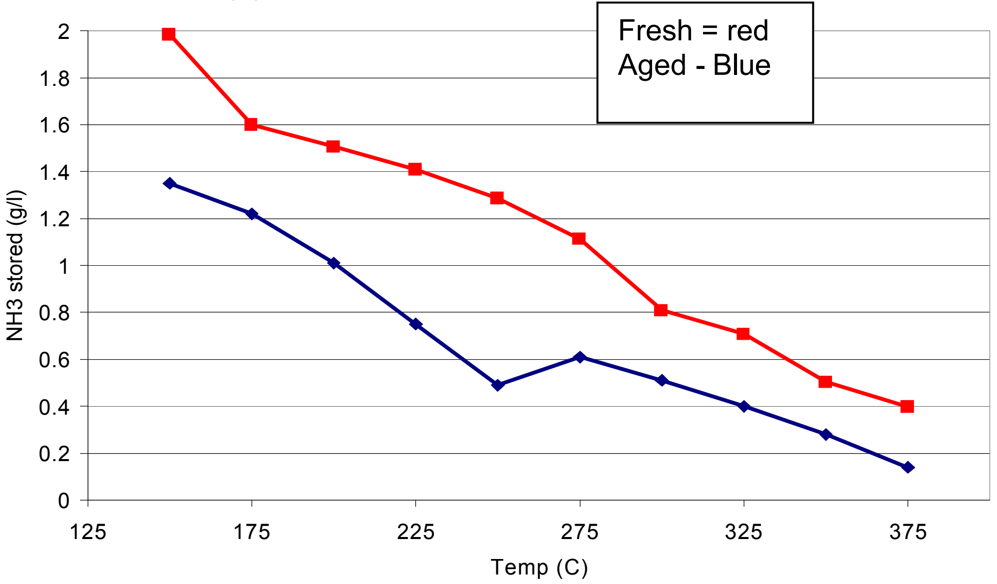

Figure 3-6: Ammonia storage as a Function of Catalyst Temperature

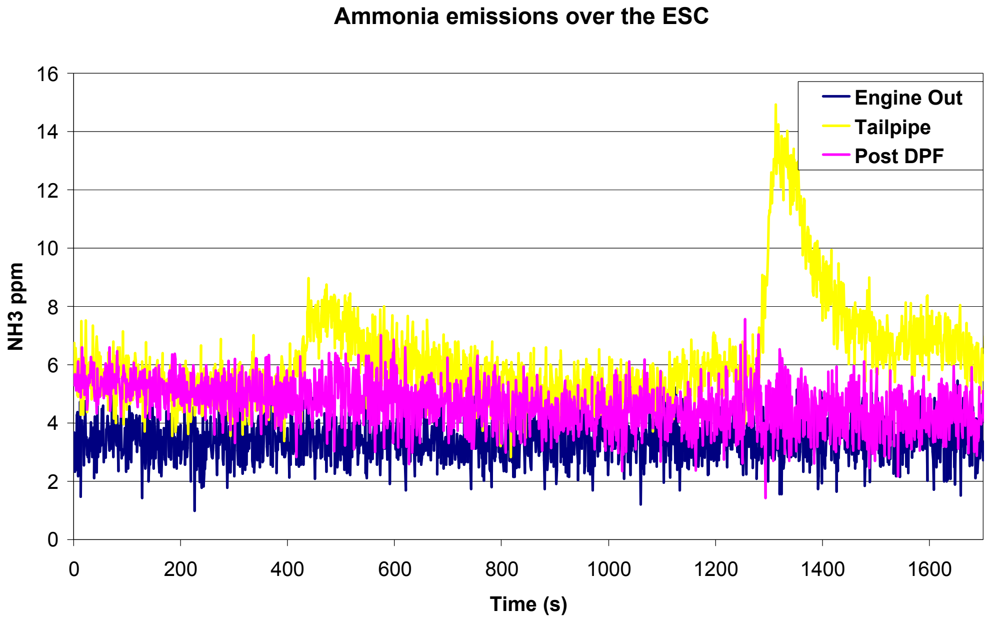

Figure 3-7: Tailpipe NH_3 emissions over ESC for Euro 6 type application

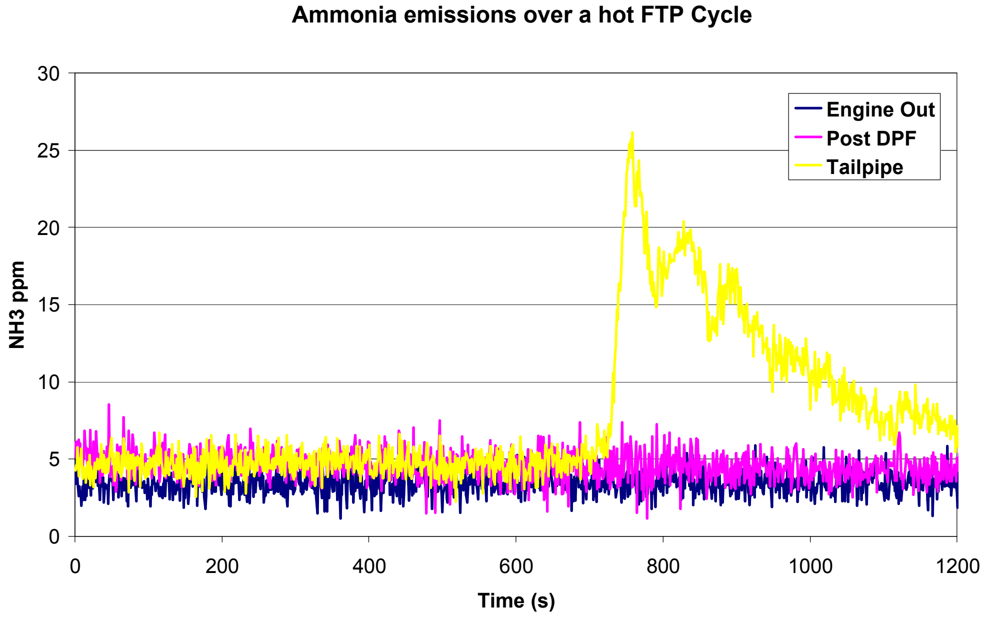

Figure 3-8: Tailpipe NH_3 emissions over the US FTP for Euro 6 type application

Ammonia slip from urea based SCR applications are removed over a clean up catalyst [8]. Figure 3-9 shows the efficiency of a clean up catalyst as a function of temperature. Above 300°C the clean up catalyst becomes highly efficient.

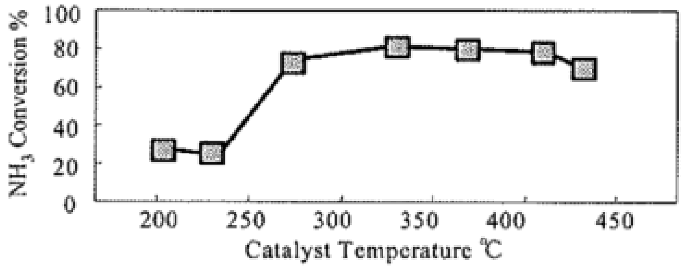

Figure 3-9: NH_3 Conversion Efficiency over a Clean Up Catalyst

Mitsubishi [9] also depicted the increase in ammonia slip as a function of NOx conversion efficiency.

Figure 3-10, shows that under transient operation the ammonia slip increases as a function of NOx conversion efficiency at a greater rate than for a steady state cycle. This is due to the increased complexity of urea injection during transients and understanding of the ammonia storage amount of the SCR catalyst.

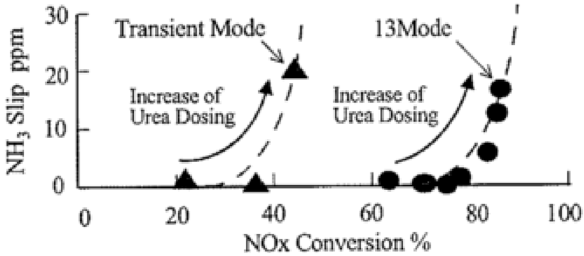

Figure 3-10: NH_3 Slip as a function of NOx Conversion Efficiency

NH_3 from LNT is produced during the rich event. Figure 3-11 shows the NH_3 emissions for a US HD application operating over the FTP cycle with a LNT[10]. During the rich event, NH_3 is produced via complete reduction of NOx with hydrogen. A downstream oxidation catalyst will potentially remove the NH_3.

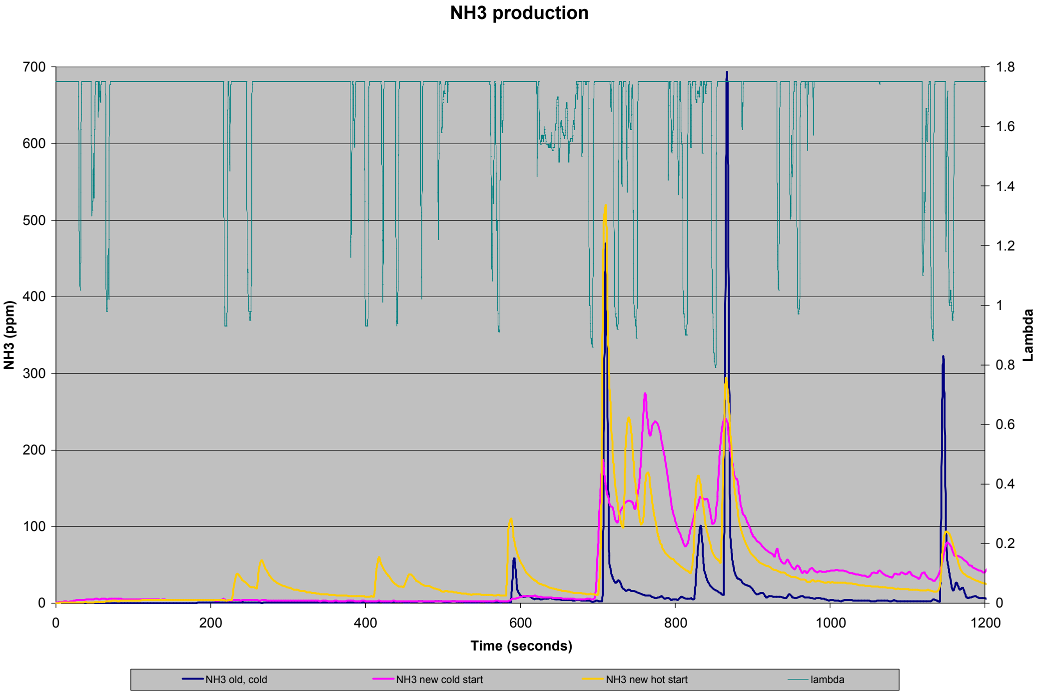

Figure 3-11: NH_3 Emissions during rich events for LNT control

3.3 NO_2 Emissions

Iveco [11] have shown how engine and aftertreatment technology has impacted tailpipe NO_2 emissions. Figure 3-12 shows the reduction in tailpipe NOx emissions with engine and aftertreatment technology. NO_2 emissions are highest when continuously regenerating trap (CRT) technology is used, which relies upon the formation of NO_2 for passive soot oxidation. For the Euro 5 with SCRT it appears that NO_2 is ~10% of the tailpipe results, which is equivalent to the Euro 3 percentage.

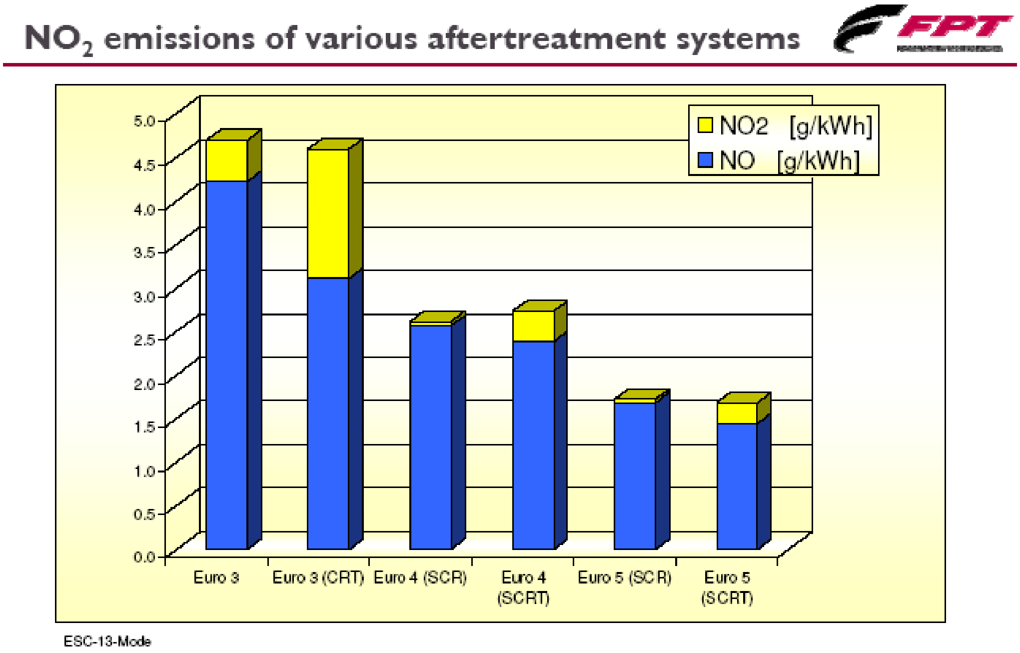

Figure 3-12: Impact of engine and aftertreatment technology on NO_2 emissions

TNO [12] have shown the impact of light duty engine and aftertreatment technology on tailpipe NO_2 emissions. Figure 3-13 shows Euro 4 technology with filters have high levels of tailpipe NO_2, >50% in some cases. This is due to highly active oxidation catalysts forming NO_2.

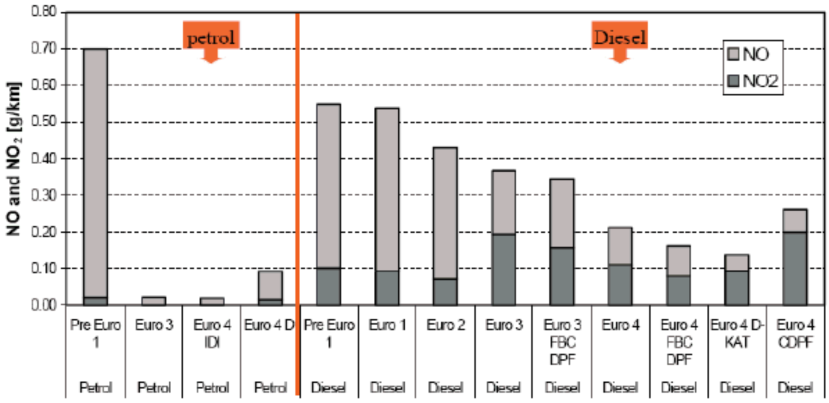

Figure 3-13: Impact of LD Engine and Aftertreatment Technology on NO_2 Emissions

Umicore [13] have investigated the impact of precious metal on NO_2 formation. From Figure 3-14 it is clear that for a fixed precious metal content using a platinum only catalyst, the production of NO_2 is higher than when a mixture of platinum and palladium is used. Currently, in Diesel exhaust aftertreatment there is a trend to increasing levels of palladium, as it is approximately 25% the cost of platinum. Therefore, potentially the post DOC NO_2 emissions will decrease with the increasing use of mixed precious metal catalysts. However, the precious metal ratio plays an important roll[14]. Figure 3-15 shows for high Pt:Pd ratio, NO_2 formation is greatest, with reduced NO_2 occurring with a low Pt:Pd ratio.

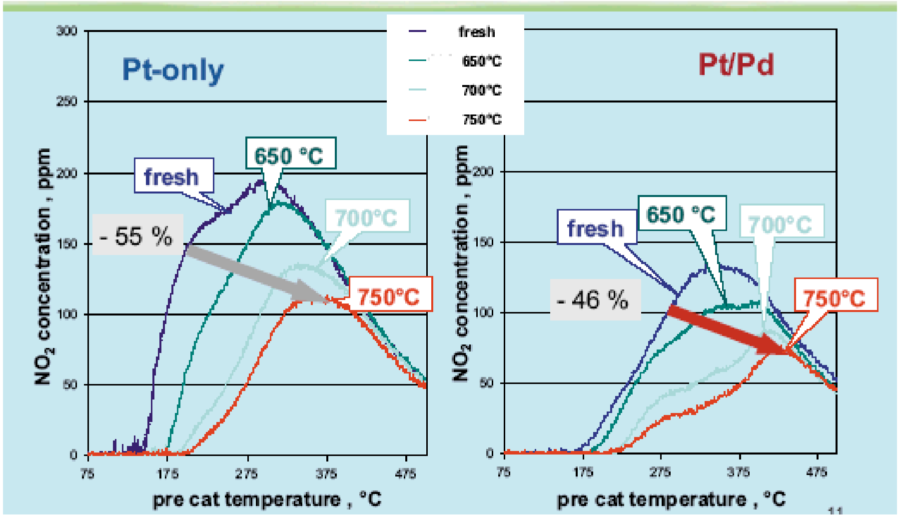

Figure 3-14: Impact of Precious Metal on NO_2 Formation

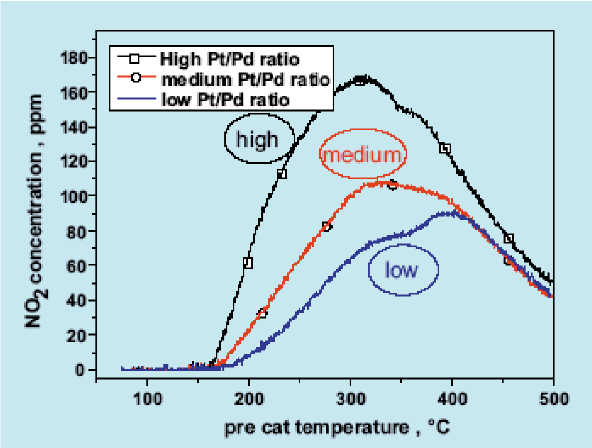

Figure 3-15: Impact of Precious Metal Ratio on NO_2 Formation

Steady state testing was performed on a Euro 3 HD engine at 2250 rpm and half load[15]. Different aftertreatment technologies, fuel sulphur levels and EGR strategies were used to determine the impact of NO_2 formation. Using a DOC and CRT gave the highest NO_2 percentage. However, the impact of using EGR or not did not significantly increase the NO_2 emissions. The use of aftertreatment had a greater effect on NO_2 compared to engine operating strategy. Table 3-1 shows the NO_2 emissions as function of engine technology and aftertreatment system used.

	Euro 3 HD Engine					
Aftertreatment	**None**		**DOC**		**DOC + CRT**	
Sulphur (ppm)	300	0	300	0	0	0
EGR	Yes	No	Yes	Yes	Yes	No
NOx	448	780	422	668	465	755
NO2	23	45	106	291	230	440
NO	422	735	312	377	235	335
NO2 %	**6**	**6**	**26**	**44**	**49**	**56**

Table 3-1: NO_2 Emissions from a Euro 3 HD Engine

Figure 3-16 follows the NO/NO_2 split through an exhaust system for a 2002 model year Cummins ISM-330 engine[16]. The engine was equipped with a DOC and a catalyst particulate filter (CPF). NO/NO_2 measurements were taken upstream of the DOC (UP DOC), downstream of the DOC (DN DOC) and downstream of the CPF (DN CPF). The results show the majority of the NO_2 formation occurs over the DOC with only minimal NO_2 formation over the CPF. The formation of NO_2 will be a function of precious metal loading and generally a DOC will have more precious metal compared to a coated filter.

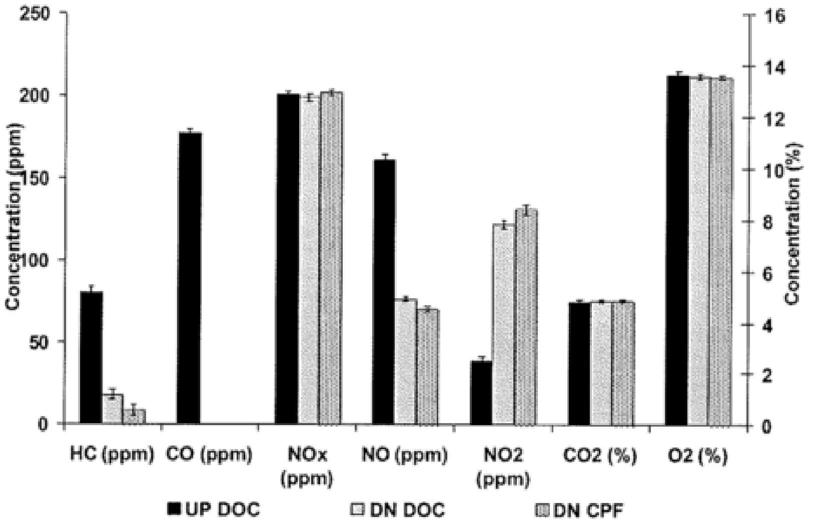

Figure 3-16: NO/NO_2 Emissions Through a HD Exhaust System

Work has been carried out to investigate the real time emissions of NOx for various applications [17]. A chase vehicle was used to measure the NOx emissions from a range of on road applications. Figure 3-17, shows the split of NO_2 and NO emissions. The application, which utilised a CRT, gave the highest percentage of tailpipe NO_2 emissions, approximately 40%.

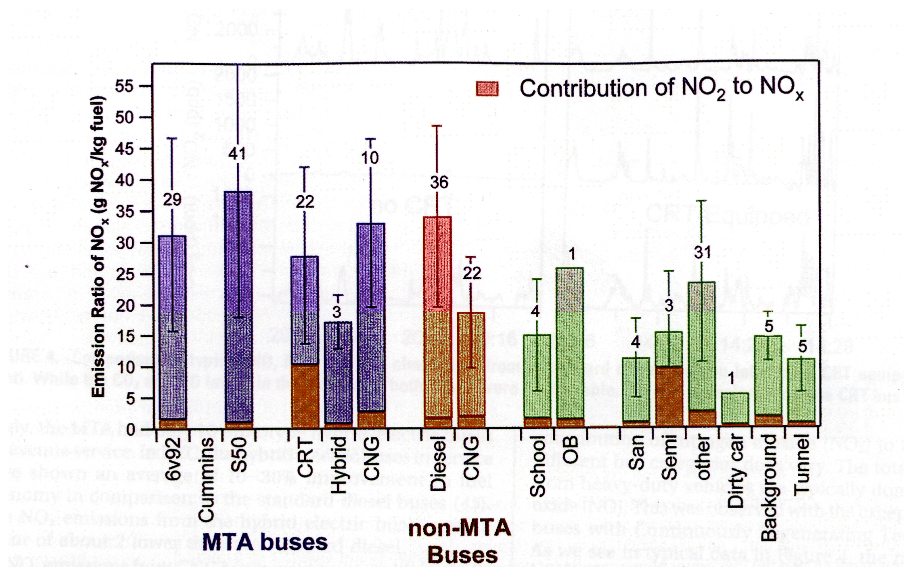

Figure 3-17: NO_2 Emissions from applications in vehicle parc (MTA = Metropolitan Transport Authority, San = sanitation trucks, semi = semitrucks)

Ricardo has investigated the impact of a clean up catalyst on NO_2 emissions for a SCR system[18]. Figure 3-18, shows that using a clean up catalyst increased the tailpipe NO_2 emissions. The formation of NO_2 over the clean up catalyst has two potential mechanisms, oxidation of NO as with a DOC or complete oxidation of NH_3, which slips the SCR catalyst.

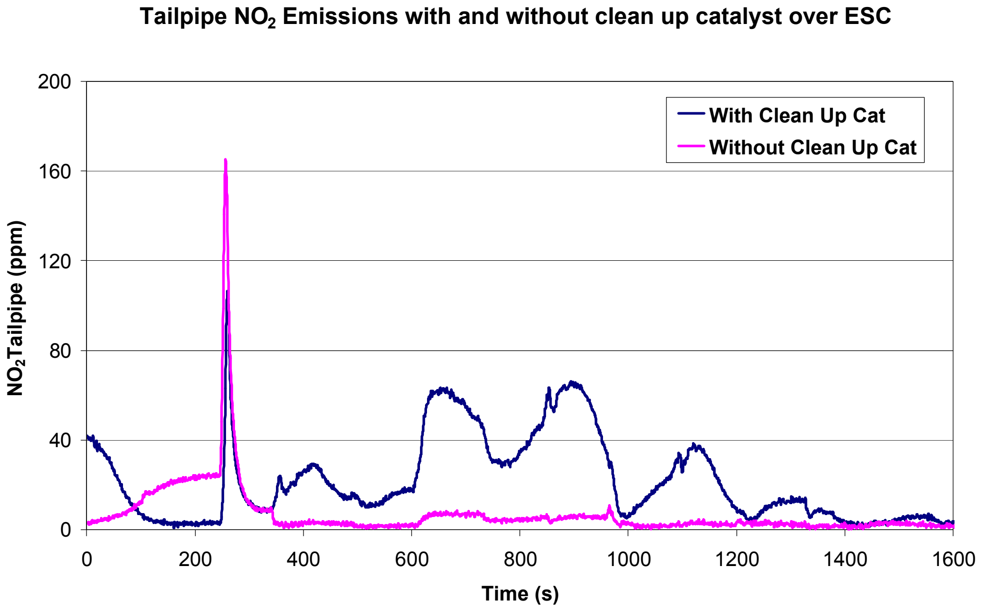

Figure 3-18: Tailpipe NO_2 Emissions with and without SCR clean up catalyst

Any catalyst, which has oxidation functionality, will produce NO_2 under the correct temperature conditions. Figure 3-19, shows data on the formation of NO_2 over a DOC in a fresh and aged condition[19]. Peak NO_2 formation occurs from 250 – 350°C.

However, ageing either via poisoning or thermal deactivation has a major impact on NO_2 formation. Therefore, it is anticipated that increasing the age of an application will decrease its NO_2 forming potential.

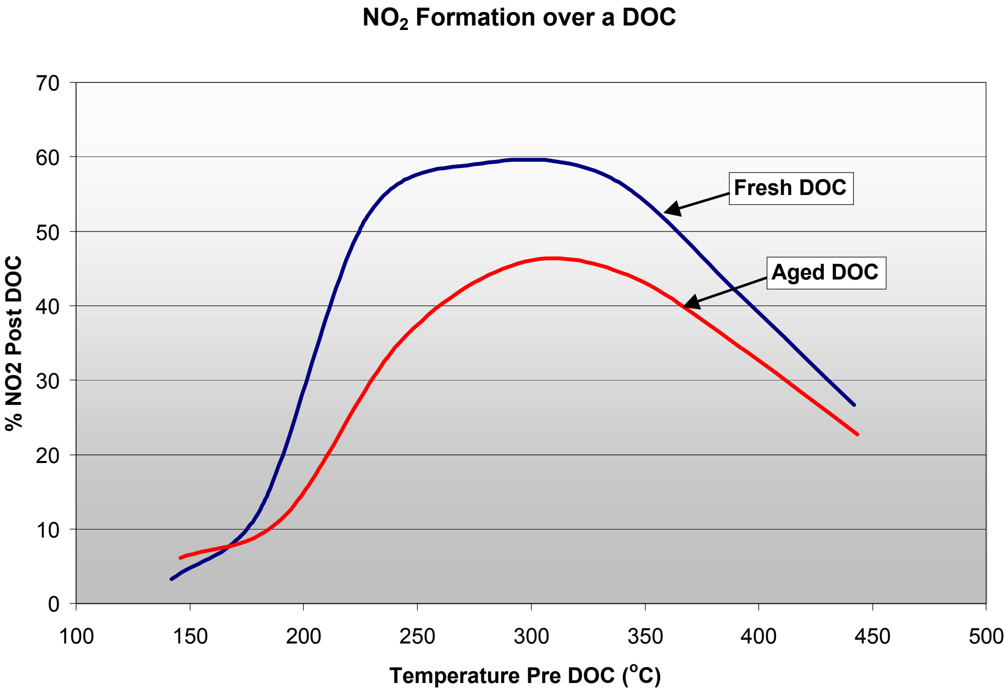

Figure 3-19: NO_2 formation over a DOC

3.4 Literature Review Summary

From the literature there was a limited amount of information relating to nitrogen based unregulated emissions from future HD aftertreatment solutions. Both LNT and SCR solutions can produce N_2O emissions via a similar mechanism via a localised rich environment either via a rich event or injection of a reductant. Ammonia emissions are most prominent for urea based SCR but ammonia also can be produced during rich events. N_2O and NH_3 can be produced over gasoline three way catalysts but reviewing gasoline technology is not part of this report. Emissions of both N_2O and NH_3 can be minimised by advanced calibration and the use of an oxidising catalyst.

Any catalyst, which has oxidising functionality, will produce NO_2 emissions. Therefore, using filters, oxidation catalysts, lean NOx traps or ammonia clean up catalysts will tend to NO_2 formation. Future HD emission solutions will use a mixture of the previously mentioned catalysts hence potentially increasing NO_2 emissions. However, NOx reduction technology, such as LNT or SCR, will remove both NO and NO_2.

From the literature, the formation of NO_2 is impacted by NOx levels and catalyst activity. Therefore, for future applications it will be extremely difficult to determine the absolute levels of tailpipe NO_2.

4 COST MODEL FOR IMPLEMENTING AFTERTREATMENT TO MEET FUTURE EMISSIONS LEGISLATION FOR HEAVY DUTY APPLICATIONS

For the cost model development two scenarios will be compared to a baseline. The scenarios are

- Baseline = Euro V
- Scenario 1 = Potential Euro VI (0.2 g/kWh NOx and 0.02 g/kWh PM) - Commission Scenario B
- Scenario 2 = Potential Euro VI (1.0 g/kWh NOx and 0.015 g/kWh PM) - Commission Scenario C
- Scenario 3 = Potential Euro VI (0.4 g/kWh NOx and 0.010 g/kWh PM) – Commissions Scenario A
- Scenario 4 = Potential Euro VI (0.5 g/kWh NOx and 0.015 g/kWh PM) – Commissions Scenario D

It is assumed that urea based SCR will be the prime route to meet future emissions limits and will therefore, be considered for this analysis for MH and HD.

Table 4-1, shows the NOx conversion efficiency and filter requirements. The baseline for the model uses a current Euro V application with SCR and no EGR. Scenario 1 is approximately equivalent to US2010 emissions limits and Scenario 2 is equivalent to 50% of the current Euro V limit. Scenarios 3 and 4 are other potential Euro VI limits under discussion.

Emissions	NOx Limit g/kWh	PM Limit g/kWh	Engine out NOx g/kWh	SCR eff %	Tailpipe NOx g/kWh	DPF	NOx to be reduced g/kWh	Adblue Required g/kWh
EU V Baseline	2.0	0.03	8	80	1.6	No	6.4	17.8
EU VI Scenario 1 equivalent to US10 Commission Scenario B	0.20	0.02	1.1	86	0.15	Yes	1.0	2.6
EU VI Scenario 2 equiv to 50% EU V Commission Scenario C	1.0	0.015	8	89	0.85	No	7.2	19.9
EU VI Scenario 3 Commission Scenario A	0.4	0.01	3	89	0.33	Yes	2.7	7.5
EU VI Scenario 4 Commission Scenario D	0.5	0.015	4	89	0.44	No	3.6	10.0

Table 4-1: Scenarios

Table 4-2, shows the technologies required to meet the baseline Euro V limits and the four scenarios meeting the potential Euro VI limits. To meet the US 2010 equivalent Euro VI, an upgraded fuel injection system with high injection pressure is required in addition to a cooled EGR circuit. The aftertreatment to meet Scenario 1 requires both SCR and DPF. The upgraded engine and aftertreatment will add significant cost to the application. Meeting Scenario 2, which is 50% of the current

Euro V limit, requires upgraded fuel injection equipment and a higher NOx conversion efficiency over the SCR catalyst. A DPF is not required to meet 0.015g/kWh PM emissions when the engine out NOx is calibrated to 8g/kWh. To meet scenario 3, the same technology is required as for scenario 1 but with a lower specification FIE and a larger SCR volume. Scenario 4 uses a partial oxidation catalyst to control PM emissions and does not require a CDPF. However, EGR and an upgraded FIE is required to assist in NOx and PM control. This scenario is marginal but gives an extreme case of what technology may be utilised.

Table 4-3, shows the catalyst volume compared to engine volume requirements to meet future emissions limits. The ratios are constant for both MD and HD applications. The SCR volume to meet Scenario 1 is lower than for the Baseline and for Scenario 2 as the absolute mass of NOx that needs to be reduced is much lower for Scenario 1. The CDPF volume is assumed to be twice the engine volume for Scenarios 1 and 3. However, increasing or decreasing the filter volume will impact the frequency of DPF regeneration events and system costs. The DOC in Scenarios 1, and 3 is for exotherm generation to assist DPF regeneration and the DOC in Scenario 4 is to produce NO_2 to assist passive soot combustion in the POC.

Scenarios 3 and 4 have SCR volumes 2.5 times the engine volume due to the mass of NOx that requires to be reduced. The POC in scenario 4 is assumed to be twice the engine volume.

Emissions	Technology
EU V Baseline	Single stage turbo
	1600 bar Common Rail System
	SCR with CUC
	NOx sensor for EOBD
EU VI Scenario 1 equivalent to US10 Commission Scenario B	EGR system + 2000bar FIE
	MAF sensor
	DPF active regen
	SCR with CUC
	NOx sensor & DeltaP sensor for EOBD
	HC injection in exhaust for DPF regen
EU VI Scenario 2 equiv to 50% EU V Commission Scenario C	Single stage turbo
	high press FIE
	SCR with CUC
	NOx sensor for EOBD
EU VI Scenario 3 Commission Scenario A	EGR system + 1600bar FIE
	MAF sensor
	DPF active regen
	SCR with CUC
	NOx sensor & DeltaP sensor for EOBD
	HC injection in exhaust for DPF regen
EU VI Scenario 4 Commission Scenario D	EGR system + 1800bar FIE
	MAF sensor
	Partial Oxidation Catalyst for PM Control
	SCR with CUC
	NOx sensor & DeltaP sensor for EOBD

Table 4-2: Technology Requirement

Catalyst: Engine volume ratio	Option 1 MD & HD	Option 2 MD & HD	Option 3 MD & HD	Option 4 MD & HD	Option 5 MD & HD
	EU V Baseline	EU VI Scenario 1 Commission Scenario B	EU VI Scenario 2 Commission Scenario C	EU VI Scenario 3 Commission Scenario A	EU VI Scenario 4 Commission Scenario D
CDPF	0.0	2.0	0.0	2.0	0.0
SCR	3.0	2.0	3.0	2.5	2.5
DOC	0.0	1.0	0.0	1.0	1.0
CUC	0.5	0.5	0.5	0.5	0.5
POC	0.0	0.0	0.0	0.0	2.0

Table 4-3: Catalyst Volume to Engine Volume Ratio to Determine Catalyst Volumes (note a cordierite filter is assumed for Scenario 1 and 4)

Table 4-4, shows the cost differential between the baseline case and the HD scenarios to meet potential Euro VI limits. The engine under consideration is a 12 litre 6 cylinder application. The HD baseline engine cost is €8300 and the aftertreatment cost including OBD sensors is €2059. Therefore, the total engine and aftertreatment cost is €10796 with 19% of the cost being for the aftertreatment.

For Scenario 1 (Commission Scenario B), the engine and aftertreatment required upgrading. The engine costs increased due to the requirement for extra EGR, improved turbocharging and an up rated fuel injection system. The engine upgrade added €2090. The aftertreatment system required the addition of a DOC and a CDPF but with a reduced SCR volume, which added €3778. In total for Scenario 1, the system costs increased by 57% over the baseline Euro V engine with the aftertreatment costs being 35% of the total costs.

For Scenario 2 (Commission Scenario C), the engine required upgrading in relation to the fuel injection system. Higher injection pressures were required to reduce the PM levels whilst maintaining high SCR NOx control. The upgraded fuel injection equipment added 12% to the system cost compared to the baseline application.

For Scenario 3 (Commission Scenario A), the aftertreatment cost is the greatest for all scenarios (38%). This is due to the requirement for a CDPF and a 2.5 times engine volume SCR catalyst. Scenario 3, has a lower cost compared to Scenario 1 due to the lower cost for the FIE.

For Scenario 4 (Commission Scenario D), similar technology to Scenario 1 is used but with 1600 bar FIE, which is a lower requirement that Scenario 1. EGR is used with 1800bar FIE and a POC is used for PM control. It is assumed that the maximum POC efficiency for PM is 50%.

The EOBD sensors costs are for a NOx, delta pressure for the filter and temperature sensors. Only Scenarios 1 and 3 require delta pressure and temperature sensors.

Ricardo Costs (€)	Option 1 12 litre I6	Option 2 12 litre I6	Option 3 12 litre I6	Option 4 12 litre I7	Option 5 12 litre I8
Scenarios	EU V Baseline	EU VI Scenario 1 Commission Scenario B	EU VI Scenario 2 Commission Scenario C	EU VI Scenario 3 Commission Scenario A	EU VI Scenario 4 Commission Scenario D
	Emissions Limit				
NOx (g/kWh)	2	0.2	1	0.4	0.5
PM (g/kWh)	0.03	0.02	0.015	0.01	0.015
	Base Engine				
Engine (€)	8300	8300	8300	8300	8300
	Catalyst				
CDPF (€)		2507		2507	
SCR (€)	1650	1350	1650	1500	1500
DOC (€)		1541		1541	1541
CUC (€)	359	359	359	359	359
POC (€)					1850
	Engine Components				
Extra EGR (€)		240		240	240
Turbocharging)€)		350		350	350
Uprated FIE (€)		1300	1300	800	400
EOBD Sensors (€)	50	80	50	80	50
MAF Sensor (€)		200		200	200
Total Increase (€)		5869	1300	5519	4431
Total Increase (%)		57%	13%	53%	43%
Total Cost (€)	10359	16227	11659	15877	14790
% Aftertreatment	19%	35%	17%	37%	23%

Table 4-4: HD Costs

Table 4-5 shows the cost differential between the baseline case and the two MD scenarios to meet potential Euro VI limits. The engine under consideration is a 6 litre 6 cylinder application. The MD baseline engine cost is €4850 and the aftertreatment cost including OBD sensors is €1408. Therefore, the total engine and aftertreatment cost is €6258 with 22% of the cost being for the aftertreatment.

For Scenario 1 (Commission Scenario B), the engine and aftertreatment required upgrading. The engine costs increased due to the requirement for extra EGR, improved turbocharging and an up rated fuel injection system. The engine upgrade added €900. The aftertreatment system required the addition of a DOC and a CDPF but with reduced SCR volume, which added €2149. In total for Scenario 1, the system costs increased by 49% over the baseline Euro V engine with the aftertreatment costs being 37% of the total costs.

For Scenario 2 (Commission Scenario C), the engine required upgrading in relation to the fuel injection system. Higher injection pressures were required to reduce the PM levels whilst maintaining high SCR NOx control. The upgraded fuel injection equipment added 5% to the system cost compared to the baseline application.

For Scenario 3 (Commission Scenario A), the engine and aftertreatment required a similar upgrade as Scenario 1, leading to a similar total cost for the 2 scenarios.

Scenario 4 (Commission Scenario D), with a POC increased the total system cost by 39% with 25% of the increase associated with the aftertreatment.

The EOBD sensors costs are for a NOx, delta pressure for the filter and temperature sensors. Only Scenarios 1 and 3 require the delta pressure and temperature sensors.

Ricardo Costs (€)	Option 1 6 litre I6	Option 2 6 litre I6	Option 3 6 litre I6	Option 4 6 litre I6	Option 5 6 litre I6
Emission Level	EU V Baseline	EU VI Scenario 1 Commission Scenario B	EU VI Scenario 2 Commission Scenario C	EU VI Scenario 3 Commission Scenario A	EU VI Scenario 4 Commission Scenario D
	Emissions Limit				
NOx (g/kWh)	2	0.2	1	0.4	0.5
PM (g/kWh)	0.03	0.02	0.015	0.01	0.015
	Base Engine				
Engine (€)	4850	4850	4850	4850	4850
	Catalyst				
CDPF (€)		1498		1498	
SCR (€)	1175	1025	1175	1100	1175
DOC (€)		771		771	771
CUC (€)	183	183	183	183	183
POC (€)					950
	Engine Components				
Extra EGR (€)		150		150	150
Turbocharging)€)		250		250	250
Uprated FIE (€)		300	300	200	100
EOBD Sensors (€)	50	80	50	80	50
MAF Sensor (€)		200		200	200
Total Increase (€)		3049	300	3024	2421
Total Increase (%)		49%	5%	48%	39%
Total Cost (€)	6258	9307	6558	9282	8679
% Aftertreatment	22%	37%	21%	38%	25%

Table 4-5: MD Costs

5 CO_2 IMPACT FOR FUTURE ENGINE AND AFTERTREATMENT TECHNOLOGY

The fuel consumption for HD/MD application is approximately 200g/kWh over the ETC for the Baseline engine as discussed in section 4. Assuming a fixed hydrogen to carbon ratio for Diesel fuel, then CO_2 emissions can be estimated from fuel consumption. Therefore, assuming Diesel fuel is $C_{12}H_{22}$ then 1g of fuel emits 3.2g of CO_2. An engine with 200g/kWh fuel consumption emits 640 g /kWh CO_2.

Upgrading the Euro V engine to Scenario 1 with advanced engine and aftertreatment technology has an approximate 10% fuel penalty due to EGR and DPF regeneration control over the ETC. Therefore the CO_2 increase over the baseline is approximately 64g/kWh.

Upgrading the Euro V engine to Scenario 2 has a negligible impact on fuel economy as the changes are mainly in increased fuel injection pressure. The fuel economy of Scenario 2 is estimated to be equivalent to the Euro V baseline.

Scenario 3 is estimated to have an 8% fuel penalty (216 g/kWh) and Scenario 4 a 4% penalty (208 g/kWh). The requirement for DPF regeneration impacts system fuel penalty.

Urea decomposition also produces CO_2. The equation below shows the hydrolysis reaction of urea to produce CO_2 and NH_3.

$(NH_2)_2CO + H_2O \rightarrow CO_2 + 2NH_3$

Figure 5-1, shows the CO_2 emissions as a function of Adblue (urea) consumption. From Table 4-1, the baseline Euro V engine consumes 17.8 g/kWh urea, scenario 1 consumes 2.6 g/kWh, scenario 2 consumes 19.9 g/kWh, scenario 3 consumes 7.5 g/kWh and scenario 4 consumes 10.0 g/kWh.

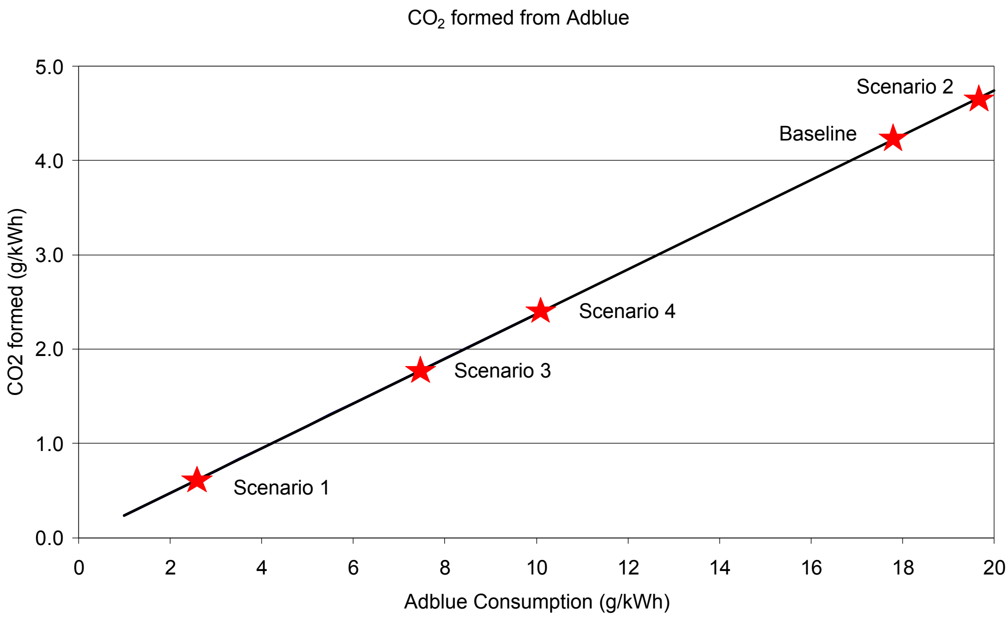

Figure 5-1: Impact of urea consumption on CO_2 formation

The urea consumption impact on CO_2 emissions for the Baseline is 0.66%, whereas, for Scenario 1 the impact is 0.09%, 0.74% for Scenario 2, 0.26% for Scenario 3 and 0.36% for Scenario 4. The CO_2 impact from urea consumption is directly proportional to mass of NOx that needs reducing.

For an accurate estimate of tailpipe CO_2 emissions for the different scenarios, the fuel consumption plus CO_2 from urea must be taken into account. Therefore, the CO_2 emission from the baseline application is 644 g/kWh, for Scenario 1 emissions are ~9% higher at 705 g/kW, 645 g/kWh for Scenario 2 is virtually unchanged, Scenario 3 has a 8% increase to 693 g/kWh and Scenario 4 gives 668 g/kWh which is a 4% increase. Table 5-1 shows the CO2 emissions for the different scenarios.

	Fuel Economy	CO2 Equivalent	Adblue Counsumption	Urea Consumption	CO2 from urea	%CO2 Increase from urea	Total CO2	%CO2 Increase over Baseline
	g/kWh							%
Baseline	200	640	17.8	5.79	4.2	0.66	644	0
Scenario 1	220	704	2.6	0.85	0.6	0.09	705	9.4
Scenario 2	200	640	19.9	6.47	4.7	0.74	645	0.1
Scenario 3	216	691	7.5	2.44	1.8	0.26	693	7.6
Scenario 4	208	666	10.0	3.25	2.4	0.36	668	3.7

Table 5-1: CO2 Emissions from the different Scenarios

6 SUMMARY

The results of the literature review show that unregulated emissions such as N_2O NO_2 and NH_3 could be emitted for both LNT and SCR technology. However, the products of reduction, NH_3 and N_2O can be controlled via calibration optimisation and the use of clean up catalysts. NO_2 can be formed over a catalyst, which has oxidation functionality at certain temperatures. The main route to NO_2 removal is to reduce the total tailpipe NOx emissions via either LNT or SCR control.

Figure 6-1 show the tailpipe NO and NO_2 emissions for a Euro VI application meeting Scenario 1 results (0.2g/kWh NOx and 0.02g/kWh PM) over the ETC[20]. The system utilised a particulate filter system and urea based SCR. On a ppm basis the NO_2 is 37% of the total NOx ppm. However, on a mass basis (due to NO_2 having an extra O molecule compared to NO) the NO_2 is 48% of the total NOx. Therefore, for this specific application (<0.2 g/kWh NOx), calibration and catalyst system the tailpipe NO_2 mass is approximately half the total.

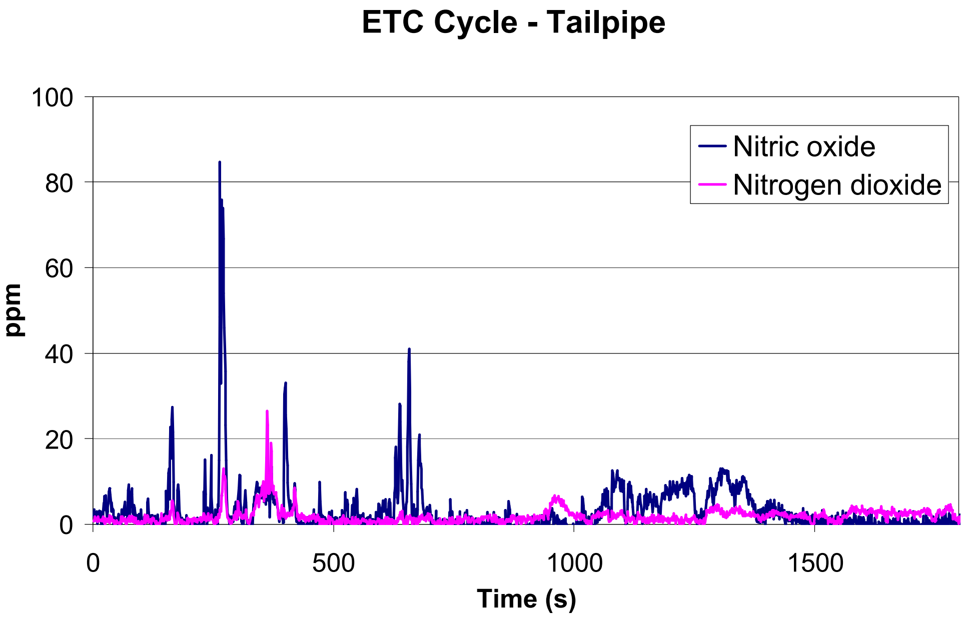

Figure 6-1: Tailpipe NO/NO_2 emissions over the ETC

Regarding cost impact of future technologies, a 57% increase in system cost over the baseline Euro V application is required to meet Scenario 1 (0.2 g/kWh NOx and 0.02 g/kWh PM) emissions for a HD application, and 49% for MD applications. The associated increase in CO_2 emissions is 7%.

A 12% increase in system cost over the baseline Euro V application is required to meet Scenario 2 (1.0 g/kWh NOx and 0.015 g/kWh PM emissions) for a HD application, and 5% for MD applications. The associated increase in CO_2 emissions is <1%.

A 53% increase in system cost over the baseline Euro V application is required to meet Scenario 3 (0.4 g/kWh NOx and 0.01 g/kWh PM emissions) for a HD application, and 48% for MD applications. The associated increase in CO_2 emissions is ~5%.

A 43% increase in system cost over the baseline Euro V application is required to meet Scenario 4 (0.5 g/kWh NOx and 0.015 g/kWh PM emissions) for a HD application, and 39% for MD applications. The associated increase in CO_2 emissions is <2%.

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Glossary of Terms

HD	Heavy Duty
MD	Medium Duty
NO2	Nitrogen Dioxide
CO2	Carbon Dioxide
NOx	Oxides of Nitrogen
PM	Particulate Matter
NH3	Ammonia
N2O	Nitrous Oxide
DOC	Diesel Oxidation Catalyst
SCR	Selective Catalytic Reduction
LNT	Lean NOx Trap
DPF	Diesel Particulate Filter
ETC	European Transient Cycle
ESC	European Steady State Cycle
FTP	Federal Test Procedure
CRT	Continuously Regenerating Trap
FBC	Fuel Borne Catalyst
Pt	Platinum
Pd	Paladium
g/kWh	grams per kilowatt hour
CUC	Clean Up Catalyst
FIE	Fuel Injection Equipment
EOBD	European On Board Diagnostics
EGR	Exhaust Gas Recirculation
MAF	Mass Air Flow