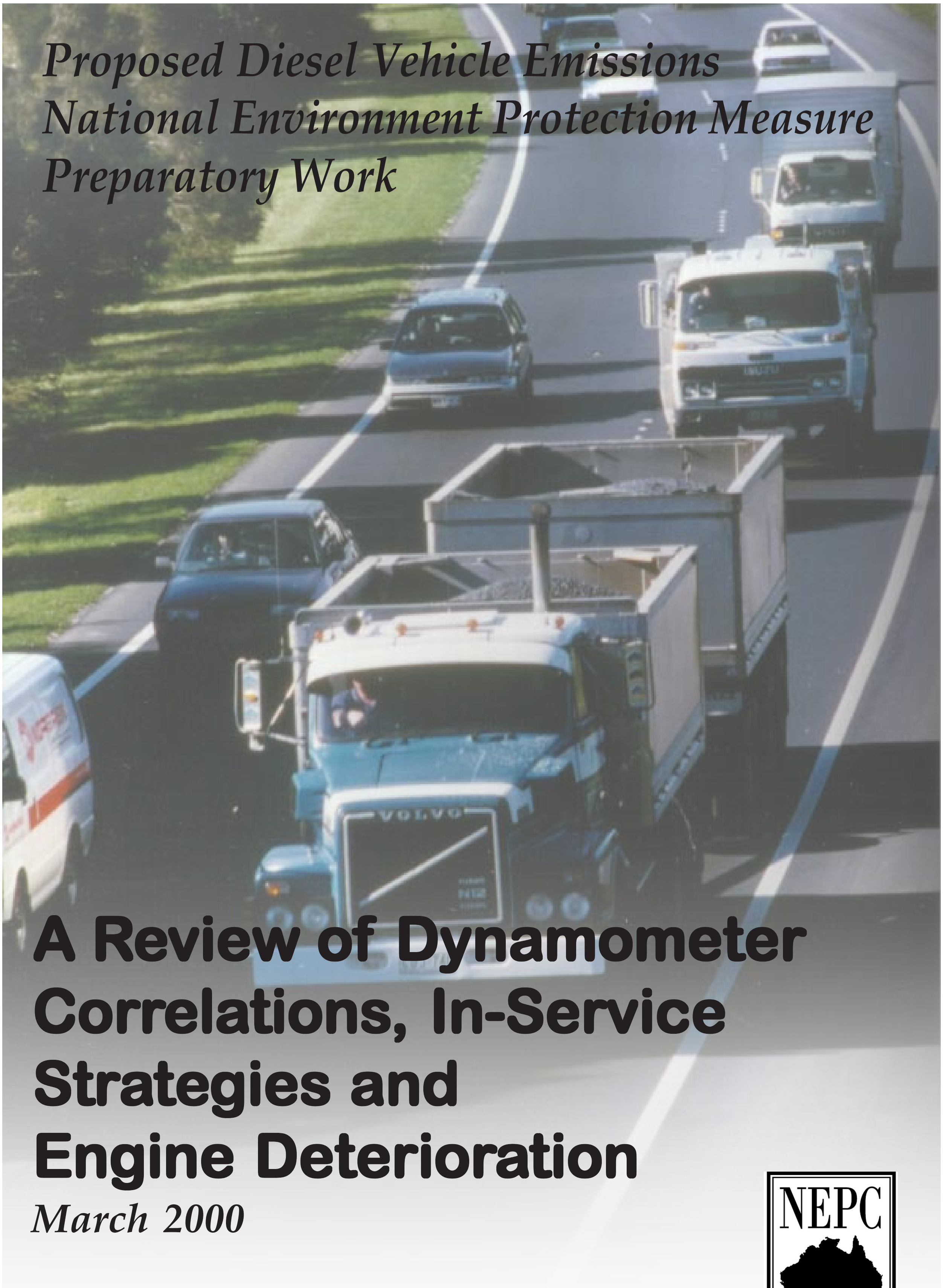


Proposed Diesel Vehicle Emissions National Environment Protection Measure Preparatory Work

A Review of Dynamometer Correlations, In-Service Strategies and Engine Deterioration

March 2000

NEPC

NATIONAL ENVIRONMENT PROTECTION COUNCIL

Prepared for the

National Environment Protection Council

by

NELSON ENGLISH, LOXTON & ANDREWS Pty. Ltd.
MANAGEMENT, TRANSPORTATION & PLANNING CONSULTANTS

P.O. Box 323, Lorne,
Vic., Australia, 3232

Tel. +613 5289 2700 Fax +613 5289 2895
Email: nelson@nela.com.au

ACN 005 065 903

in association with

Energy and Environmental Analysis Inc.

ISBN 0 64232 322 4

A suite of projects have been developed during the preparatory work for a proposed Diesel Vehicle Emissions National Environment Protection Measure. These projects are:

The Australian Diesel Fleet Existing Vehicle Characteristics and the Modelling of Transport Demand, Vehicle Populations and Emissions

In-Service Emissions Performance - Phase 1: Urban Drive Cycle Development

In-Service Emissions Performance - Phase 2: Vehicle Testing

In-Service Certification Correlation Studies

A Review of Dynamometer Correlations, In-Service Emissions and Engine Deterioration

In-Service Emissions Testing – Pilot Study, Fault Identification and Effect of Maintenance

Major funding for these projects has been provided by Environment Australia. The other contributing agencies are the Department of Transport and Regional Services, NSW Roads Traffic Authority and the National Road Transport Commission.

Electronic copies of these documents are available from:

National Environment Protection Council Service Corporation
Level 5, 81 Flinders Street
Adelaide, SA 5000

Telephone: (08) 8419 1200
Facsimile: (08) 8224 0912

These documents are also available online: http://www.nepc.gov.au

CONTENTS

EXECUTIVE SUMMARY

INTRODUCTION

The National Environment Protection Council (NEPC) is undertaking a critical examination and assessment of emission from diesel engine powered vehicles in Australia. There is worldwide interest in the methods to test heavy-duty diesels for emissions, and in the emissions from diesel in-service vehicles. The NEPC has issued two projects to study these issues. The first (Project 5) is to conduct a critical examination of the literature and on-going efforts to establish a correlation between measured emissions on a chassis dynamometer and on an engine dynamometer for heavy-duty vehicles. The second (Project 6) requires an examination of the emission deterioration under in-service conditions for both light-duty and heavy-duty diesel vehicles. This project also requires an examination of regulatory and non-regulatory programs to maintain emissions at certification levels.

Since both projects require an understanding of emission standards and test methods, these topics are covered under a common background section. Details specific to each project are covered in separate sections.

BACKGROUND ON EMISSION STANDARDS AND TEST PROCEDURES

Australia imports all of its heavy-duty diesel engines from three sources: Japan, Europe or the U.S. Japanese engines are used in most of the lighter vehicles (around five tons GVM) and in about half the vehicles in the ten to 15 GVM range. European diesels account for the other half of this range, while European and U.S. diesels engines power the larger vehicles over 15 tons GVM. Australia did not require these engines to meet any criteria pollutant emission standards until 1996, and has adopted European ECE R49/02 standards since that time. The Australian regulation also allows alternative certification to U.S. 1991 and later standards or Japanese 1994 and later standards.

Since the Australian heavy-duty engine market is not large, it is unlikely that engines were especially designed for Australia. Most Australian engines are likely to have technology equivalent to the country of origin model, but some may be recalibrated for increased fuel efficiency and, hence, increased NOx emissions.

For a variety of reasons, heavy-duty emissions regulations are based on testing engines as opposed to entire vehicles. A detailed survey of emission standards and test procedures showed that U.S. heavy-duty diesel engine emission standards have been and are the most stringent in the world, while European and Japanese standards have lagged U.S. standards by about five years. However, by 2008 the U.S., Japanese and European standards are likely to be harmonised and achieve near parity.

It should be noted that even the U.S. standards were relatively lax until 1988, and even the highest emitting engines could meet pre-1988 standards with modest technological changes. This is also true for European and Japanese standards to the early to mid-1990s. Hence, most engines certified to these standards had emissions far below the standards, and the standards were not binding.

Engine test procedures also varied between the U.S., Europe and Japan. Until 1984, all three utilised a steady-state engine test called the 13-mode test, although the individual mode definitions varied between the three. Since 1984, the U.S. has used a more complicated transient cycle based test that more closely replicates the engine's duty cycle during typical driving.

European and Japan have continued to use the 13-mode test. Starting in model year 2005, European regulations will require both a transient test (different from the U.S. transient test) and a revised 13-mode test. The U.S. has also proposed re-incorporating the 13-mode test along with the existing transient test starting in model year 2004.

The need for a transient cycle based test procedure has been debated extensively, but it is now acknowledged that at very low emission levels, the transient test provides a significantly better indication of on-road emissions than any steady-state test. At higher emission levels more typical of engines built until the late 1980's in the U.S. or early 1990s in Europe, the steady-state test procedure could be used to provide a reasonable indication of criteria pollutant emissions, with the possible exception of particulate mater (PM). However, PM standards for heavy-duty engines were not effective until the late-1980s or early 1990s.

Light –duty diesel vehicles are currently popular in Europe but not in the U.S. or Japan. These vehicles have been certified using procedures and standards that were and are similar to those for light-duty gasoline vehicles. As with heavy-duty diesels, the emission standards applicable to diesel vehicles were relatively lax and standards to 1992 were easily met by most vehicles. Since 1992, the introduction of PM standards has resulted in some difficulty in meeting these standards, but standards for gaseous emissions continue to be not binding. However, it should be noted that diesel car sales are very low in Australia, and most light-duty diesels sold are in light commercial vehicles or in four-wheel drive utility vehicles. Commercial vehicles generally employ smaller or derated versions of heavy-duty engines used in trucks of 3.5 to 7 tons GVM. Four wheel drive utility vehicles use unique large displacement light duty engines.

The findings of the background analysis that are important to the two NEPC projects are:

- Australia had no emission standards for criteria pollutant emissions from heavy-duty engine until 1996, so that emissions of heavy-duty engines imported prior to 1996 is not well understood.
- Most engines imported from Europe or Japan until the early to mid-1990s had emission levels that were well below applicable standards in those countries.
- The steady state engine based 13-mode test is the reference emissions test for the majority of heavy-duty engines imported to Australia. Only engines imported from the U.S. (which are not a sizeable fraction of the Australian heavy-duty fleet) were certified based on a transient test.
- In the future, as emissions standard are increased in stringency, certification will require use of both the 13-mode steady-state test and transient test in Europe and the U.S.
- The light duty diesel fleet in Australia is not similar to the light-duty diesel fleet in Europe. It consists of larger displacement light-duty engines or smaller versions of heavy-duty engines.

NEPC PROJECT 5

This project had two objectives. The first was to conduct a critical examination of the literature and on-going efforts to establish a correlation between measured emissions on a chassis (vehicle) dynamometer and on an engine dynamometer. The second was to provide advice on methodologies for establishing such correlation in Australia, with an assessment of the level of confidence that can be applied to such correlations.

Types of Cycles

A comprehensive review of the available chassis test cycles was performed. Until the early 1990s, there was virtually no interest in replicating the engine based 13-mode steady-state test on a chassis dynamometer. The 13-mode test consists of a series of engine RPM and torque operating points (or modes) over which emissions are measured. Since about 1992, the replication of this test has been extensively investigated in Europe. In principle, this replication is very straightforward, but the major difficulty is in determining engine torque output when the engine is in the vehicle. Two methods were developed, one based on engine fuel consumption, and the second based on calculation of power loses in the vehicle transmission, driveline and tyres. Both methods have been successfully developed in Europe.

Transient test cycles have been for more widely used in chassis dynamometer based testing. Two types of cycles exist that we have labelled as “geometric” and “realistic”. Geometric, or stylised, test cycles obtain their name from the fact that the speed versus time trace appears as a series of straight lines that reflect constant acceleration rates, constant speed cruise and constant deceleration rates. Realistic cycles are derived from actual driving traces where speed and acceleration rates vary continuously over time. Several geometric cycles have been widely used historically, and these include the Society of Automotive Engineers J1376 test procedures and the West Virginia ‘Five Peak’ cycle. Realistic cycles have been historically limited to the U.S. EPA Transient Test (derived from the same data as the engine based transient test) but other cycles are under development. In this context, the newly developed Australian Composite Urban Emission Drive Cycles (CUEDC) are classified as “realistic”.

The major drawback to most chassis based transient cycles is the fact that the cycles are invariant with engine characteristics, whereas engine based cycles are defined in terms of the engine’s maximum torque and RPM ratings. Hence, a truck of a given weight (GVM) with a powerful engine is not subjected to accelerations requiring full engine power during a chassis test, while an underpowered truck may have difficulty keeping up with the specified driving trace. The lack of scaling is a major drawback and this problem could also effect the newly developed CUEDC. There are research programs in the U.S. to develop a cycle whose specification scales with the test vehicle’s power-to-weight ratio. Preliminary results from such efforts are promising, but more work is required before such cycles can be universally adopted.

Correlations Between Engine and Chassis Tests

The topic of correlations between engine and chassis based tests is complex because of the many sources of variability in emissions. The sources include:

- engine cycle-to-cycle variability;
- engine-to-engine production variability;
- emissions measurement instrument variability;
- drive cycle variability;
- driver variability.

When comparing results from two different engines of the same model type, all of the above sources of variability come into play and total variability can be large.

Manufacturers have attempted to measure the correlation of emission from different test cycles conducted on engine dynamometers. In general, there is agreement that NOx emissions can be correlated between transient tests and steady-state tests, but the correlation for PM emissions is poor at low emission levels. The coefficient of variation (COV) for NOx emissions across the two cycles is in the order of ten percent, for the same engine and laboratory.

European testing to compare results from the engine based 13-mode test with the chassis based 13-mode test show that very good correlations have been established. Experienced test laboratories have obtained average emission correlations with a COV of two percent, and a maximum error for any pollutant of less than five percent. However, engines with very low emissions have not been examined, and it is possible that the COV could be higher due to the difficulty in measuring low concentrations of pollutants. More limited testing in Japan has also achieved good correlations of the Japanese 13-mode test (which is different from the European 13-mode test).

U.S. testing to compare the results from the engine based transient test and the chassis based EPA transient test have had mixed success so far. Reasonable correlations have been achieved if the chassis test forces acceleration at near full power and the truck can follow the specified speed/time trace with limited error. However, underpowered or overpowered trucks result in relatively poor correlations. As noted, these has been some recent progress in developing a chassis based test that “scales” with the truck power-to-weight ratio. However, testing is too limited to date to provide meaningful COV values. Moreover, there are numerous transient test specifications that are currently undefined and set by each laboratory in an ad hoc manner. It should be noted that the Australian CUEDC would have similar problems in the field unless it can be scaled to truck characteristics.

There has also been some attempt to reproduce the engine based transient cycle on a chassis test by hooking up a dynamometer to the axles and conducting the entire test in one e gear. The axle dynamometer arrangement is similar to the engine dynamometer arrangement except that it cannot provide motoring torque (i.e., use the engine in a braking mode). Limited results to date have been disappointing because of poor PM emissions correlation.

Establishing Correlations in Australia

The survey of the state-of-the-art for establishing correlations shows that:

- good correlations between engine and chassis based emission test results can be obtained for the 13-mode test except, possibly at very low emission levels;
- correlations on transient tests are far more difficult to obtain, largely due to the way chassis transient tests have been specified (or not specified).

In general, the steady-state procedure can be reproduced on either a roll based chassis dynamometer or an axle dynamometer, but we do not wish to imply that achieving a high degree of correlation is easy. There are many issues that Australia will need to resolve for implementing the steady-state test, including:

(1) The test points (in terms of engine RPM and torque) must be obtained from the type approval certificate. Such certificates are not available for U.S. engines (since there is no 13-mode test requirement) and may not be available for Japanese engines;

(2) The determination of engine torque using the fuel consumption method requires an engine map that may not be readily available. Moreover, some assumption must be made on the state-of-tune of the engine, and this can lead to significant error.

(3) Determination of engine torque using the power loss estimation method must rely on empirical formulae to estimate drivetrain losses. European formulae may not be applicable to Australian vehicles.

(4) There may be no easy way to check the correlation because even engine test facilities are very limited in Australia, and such facilities have not been audited by any experienced agency.

(5) In the absence of any simple method to resolve these issues, correlations in Australia may not achieve the levels attained in Europe.

Correlation issues for transient tests are substantially more complex, and Australia should be prepared to address the "scaling" issues in terms of adapting the drive cycle to truck specifications. It is also believed that axle dynamometer based measurements where the system cannot simulate motoring of the engine may result in very inaccurate results for PM emissions. It is recommended that Australia monitors U.S. developments in transient cycle specifications and addresses these issues in the context of the CUEDC in the future.

NEPC PROJECT 6

This project had three main objectives. First, the in-service emissions deterioration rates for both light-duty and heavy-duty diesels were critically examined. Second, we examined worldwide emission control programs that are designed to maintain engine emission performance at original levels over its useful life. Third, programs that are related to improving the emission performance of in-service vehicles (through retrofit of control technology or upgrade at the time of engine rebuild) were examined. The applicability of both types of programs to Australia was assessed, based on the data from existing programs.

Emissions Deterioration

The emissions deterioration of heavy-duty diesels has not been studied extensively largely due to the lack of adequate test facilities, and the expense involved in recruiting and testing a sample of in-use trucks. There is also a widespread belief that the emissions of heavy-duty diesel engines are relatively stable over their useful life.

Since the late-1980s, there has been a growing realisation that in-service diesels do not maintain certification level emissions over their useful life. There are several components to the in-service emissions deterioration, or "excess" emissions that occurs. First, even in the certification process, emissions are assigned a deterioration factor based on an idealised durability cycle, and the real world duty cycles imparts somewhat larger deterioration in emissions relative to the certification durability test. Second, the levels of maintenance recommended by the manufacturers are usually not strictly followed, causing additional deterioration. Third, there may be mal-maintenance (either intentional or unintentional) due to mechanic inexperience. Fourth, there may be intentional tampering, usually to increase horsepower or fuel economy. Lastly, there may be design defects in the emission control system that causes high emissions.

Emissions deterioration is also defined in several ways. One definition is the emissions of in-service diesels with respect to the emissions standard to which a particular engine is certified. The second defines deterioration with respect to the increase in emissions relative to emissions when an engine is new and properly tuned. These definitions can cause substantial differences in the findings on deterioration largely because many engines have been certified at emission levels well below standards, and even a significant increase in emissions will not cause an exceedance of standards. Indeed, this is the situation with many of the study results from Europe.

Significant testing of in-service trucks has been conducted in the Netherlands, Germany and the UK, with some limited testing in Sweden. Most of these tests have been conducted on vehicles with engines certified to the 88/77/EEC standard or the Euro I standard, with a few certified to the Euro II standard. Vehicles were typically 4 to 5 years old at the time of testing (except for the engines certified to the Euro II standard). No vehicles were found to exceed the 88/77/EEC standard partly because the standard was not very stringent. Analysis of the data on vehicles with engines certified to the Euro I or II standard showed about 5 to 10 percent of vehicles exceeding standards for one pollutant, and up to 15 percent exceeding standards for any pollutant. Observers in Europe believe that tampering and mal-maintenance are low in Europe, but the sampling process for the in-service emissions testing conducted is potentially biased in favour of clean well-maintained trucks.

There has been some testing of in-use diesels in Germany and Netherlands in the 1980s. As with heavy-duty diesels, applicable standards prior to 1992 were not very stringent and virtually no vehicles were found to exceed standards. There has been only limited testing in the 1990s, and a test of 28 diesel light-duty vehicles in Germany that were certified to Euro I levels found that three vehicles exceeded PM standards and only one of the three exceeded the standards by a large amount. Gaseous emission standards were met by all vehicles. However, the relevance of these findings for Australia is limited because the light-duty fleet is not similar to the one in Europe.

Little testing has been done in the US, with only one major program on heavy-duty engines conducted in the 1980s. Statistical analysis of the data showed that at the end of an engine's useful life of about 500,000km, HC emissions increase by over 70 percent and PM emissions increase by over 80 percent, on average, relative to emissions when new. (This does not compare emissions with standards and is a different measure of deterioration then the one discussed for Europe). A completely different approach to estimating emissions deterioration has also been used in the US. This method relies on finding the mal-performance rates of emission controls by diagnosing a large number of in-service vehicles, and modelling the emissions deterioration by associating each mal-performance with an incremental emissions impact. Interestingly, this approach resulted in a similar finding as the statistical approach for engines manufactured in the late 1970s to early 1980s. For newer engines, especially those featuring electronic controls, the mal-performance rates are lower, but the percentage increase in emissions due to mal-performance is larger. This is partly because of the low absolute emission rates and partly because modern engines are so highly tuned for best emissions that mal-performances cause a larger percent increase in emissions than for older engine designs.

Some observers believe that the European tampering and mal-maintenance rates are much lower than American rates and that in-service emissions deterioration is a bigger problem for the US than for Europe. It is not clear what the situation in Australia is, and we could find no objective evidence of the situation being closer to Europe or the US. Nevertheless, the modelling approach allows an assessment of the situation at reasonable cost, and is recommended for Australia.

Control of In-service Emissions

The maintenance of emissions by inspecting in-service vehicles is used widely, although many programs are using test methods that may be not be effective, or are completely ineffective at worst. Much of the motivation for subjecting heavy-duty vehicles to inspection/maintenance programs is the public perception of diesel smoke, as well as the real threat of the carcinogeniety of smoke particulates. Virtually all of the ongoing programs to control in-service emissions have focused on smoke emissions, and the accompanying reduction (or increase) in gaseous emissions as a result of reducing smoke has not received any attention except in isolated cases. Indeed, outside of analyses conducted by California in the early-1990s, we have not been able to find any attempt to characterise the other benefits of smoke reduction programs that are now in place in most OECD countries.

Seven states in the U.S. currently have active heavy-duty I/M programs with two others operating pilot programs. All EC countries and Japan have truck inspection programs although the quality varies widely between European countries. Virtually all programs are based on smoke emissions as an indicator of pass/fail status.

Light-duty diesel vehicles are also subject to inspection and maintenance programs in most OECD countries. In the US and Japan, many local jurisdictions use tests similar to those employed for petrol vehicles, even though the tests are irrelevant to a diesel. In some states in the US and in most locations in Japan and Europe, light duty diesels are also subjected to a smoke test.

A typical I/M program consists of standardised test and measurement procedures, a set of pass/fail cutpoints, and an enforcement mechanism. Smoke tests can be loosely categorised into two types: transient and steady-state. Transient tests measure smoke over a changing engine speed and load cycle, while steady-state tests measure smoke during a constant speed and load condition. Each can be effective in detecting certain typical engine mal-performances although transient tests are generally more robust in terms of the scope of mal-performances identified.

The most common test procedure currently applied in the U.S. to heavy-diesels is the SAE J1667 snap acceleration test procedure, recently promulgated by the Society of Automotive Engineers. This test procedure was jointly developed by the regulatory and trucking communities and specifically addresses industry concerns with its predecessor J1243 test procedures. Light-duty diesels have not been of much concern in the US due to the small population.

In general, transient testing provides an effective means of identifying the short duration smoke events that characterise a variety of common mal-performances. On the other hand, steady-state tests at wide-open throttle (i.e., lug down) do not identify several common mal-performances, but identify some mal-performances that the transient tests do not. These mal-performances are not as common, but can have a significant emissions impact. The idle and cruise mode tests are largely ineffective in detecting most mal-performances, since they are conducted at part throttle.

Most EC countries also use the snap acceleration test (sometimes call free acceleration test) for both light-duty and heavy-duty diesels though some regional jurisdictions in Germany require both the snap acceleration test and the lug-down test. The European snap acceleration test is not identical to the J1667 in terms of meter response time and technical criteria to determine a valid test, and these specifications also very from country-to-country. For example, Germany has a time specification for the RPM increase on the free acceleration test, while France does not.

The largest difference between the U.S. and Europe is that the smoke opacity standards in many the EC countries are type specific and vary from engine model to engine model. The standards are actually suggested by the engine manufacturer, leading to considerable complexity in administration. Moreover, the engine manufacturers have an incentive to make the standards relatively lax, so that so engines with marginal mal-performances are not failed.

In Japan, the free acceleration test is also used, but the smoke measurement is based on a long averaging time instrument so the results are not comparable to the SEA J1667 test. However, Japan implements a standard of 40 percent opacity for pre-1999 trucks, and 25 percent opacity for 1999 and later vehicles.

While detailed failure rates for EC countries and Japan are not available, several leading researchers confirmed to EEA that only about one percent of vehicles (light or heavy) tested actually fail the test. Hence, the primary value of the test appears to be as a deterrent to tampering in Europe and Japan. Failure rates are somewhat greater in the U.S., but still quite low given the number of smoky trucks observed usually on the road. Only the California Roadside Program has addressed the issue of targeting likely failure for the test, and is hence more effective. Since high smoke emitters can be usually identified, to targeting of potential failures is quite easy.

Analysis for California shows that the I/M program is capable of identifying at least half of all “excess” emissions of HC and PM on older mechanically controlled engines. No recent analysis has been done on the benefits for newer electronically controlled engines, but the absolute quantity of excess emissions as well as the percent identified have undoubtedly declined relative to older engines. The high level of excess emission may be a phenomenon that is U.S. specific, since the rates of tampering and mal-maintenance are potentially much higher in the U.S., relative to European levels.

Retrofit and Rebuild Related Programs

The potential to decrease emissions of in-service diesels through retrofit of new technologies to older vehicles or by rebuilding engines to new standards has received considerable attention in Europe and the U.S. over the last five to seven years.

To date, there are no regulations in Europe requiring the retrofit of technologies or the rebuilding of engines to more stringent emissions standards. The EC regulation only requires that rebuilt engines meet the original specification that the engine was designed to; the same regulation applies to re-engined vehicles. However, in the case of re-engined vehicles, we understand that most operators in Europe simply buy a current model engine of the same make, so that an upgrade occurs ‘defacto’ simply due to convenience.

While there are no requirements that legally enforce retrofit or upgrade, there are many organisations in Europe that are voluntarily retrofitting engines with newer technology, mostly trap oxidisers or oxidation catalysts. The vast majority of these voluntary retrofits have been by the Metropolitan Transport Organisations (state-owned) for the bus fleet.

The retrofit devices are commercially offered by catalyst manufacturers, such as Engelhard and Johnson-Matthey. Each country is certifying retrofit devices to meet a minimum performance requirement that requires a reduction in PM of at least 20 to 25 percent and HC by a similar amount, without increasing NOx emissions or noise.

Virtually no assessment of programs that aim at reducing NOx emissions from in-service vehicles has occurred in Europe. NOx can be reduced from in-service engines by a number of actions ranging from injection pump and injection timing recalibration to the addition of an air-to-air intercooler in non-intercooled or jacket water intercooled engines. We are unaware of any European program that has focused on these aspects, although there is a white paper to be released shortly in England that may discuss such issues.

Sweden is using a novel method to encourage the retrofit or upgrade of engines. It has created environmental zones in its three largest cities: Stockholm, Goteburg and Malmo. The zone essentially covers the entire central business district of the cities. Within these zones, municipal councils have the right to restrict heavy-duty diesel vehicles that do not meet stringent emission standards or are retrofitted with approved devices. Conversations with environmental authorities of Stockholm and Goteberg confirmed that many older buses are now fitted with Level A devices and a few with Level B devices. There has been a redirection of newer trucks to the environmental zones, but authorities believe that several hundred private trucks have adopted retrofit devices in all of Sweden. Hence, it is regarded as a relatively successful local air pollution control strategy.

The U.S. has moved ahead on some specific retrofit and rebuild requirements that are now part of the regulations. There are four major actions that now affect retrofit and rebuild in the U.S.:

1. retrofit and rebuild requirements for 1993 and earlier urban bus engines;
2. the California Low Emission Vehicle Emissions Credit Program;
3. the North-Eastern States Voluntary Heavy-Duty Retrofit Program;
4. the Low NOx Emissions Rebuild Program.

Of these, the first and last programs are driven by regulatory requirements, while the California and North-Eastern State Program are market driven approaches.

In early 1993, EPA published final Retrofit/Rebuild Regulations for 1993 and Earlier Model Year Urban Buses. The regulations require affected urban bus operators to comply with one of two program options, beginning January 1, 1995. Option 1 established particulate matter (PM) emission requirements for each urban bus in an operator's fleet when the engine is rebuilt or replaced. Option 2 is a fleet averaging program that sets out specific annual target levels for average PM emissions from urban buses in an operator's fleet. The two compliance options are designed to yield equivalent emissions reductions for approximately the same cost.

Certification activity under the retrofit program has lagged substantially behind the schedule anticipated by EPA when the final rule was promulgated. No equipment was certified when EPA revised the post-rebuild levels based on equipment. EPA's assumption that certification activity would begin early was incorrect and more importantly, EPA's assumption that certification activity would be complete by mid-1996 was incorrect. For example, EPA only recently certified equipment manufactured by Engelhard Corporation that triggers the 0.10 g/bhp-hr (0.13 g/kWh) standard for 1979 though 1989 model year Detroit Diesel Corporation (DDC) 6V92TA MUI engines. Additionally, Johnson Matthey Incorporated has been certified to supply equipment to the same standard, and applicable to these, and other, DDC engines. There are other plans for certifying equipment to the 0.10 g/bhp-hr (0.13 g/kWh) standard for a large segment of the bus engine population. Hence, the program has little impact to date

The California and North Eastern States programs are similar in that they involve the use of emission credits that can be generated by retrofitting a diesel engine. In the U.S., most major metropolitan areas are not yet in compliance with the air quality requirements for ozone and are designated as non-attainment areas. In these areas, businesses that generate more emissions than some allowable level are required to offset the increase by purchasing credits or helping reduce emission elsewhere, making emission reductions a marketable commodity. Hence, there is value to a private firm reducing emission by retrofit, and selling these credits can (in theory) offset the cost of retrofit either partially or entirely. To date, however, the number of voluntary retrofits has been very small (a few hundred vehicles nationally) largely because the cost of retrofit is very much higher than the market value of the credits.

The newest program is one that has come about from a settlement of a regulatory action by EPA against the diesel engine manufacturers. The US EPA believed that modern diesel engines employed "cycle beating" techniques to met current emission standards, and initiated legal actions against engine manufacturers. As part of the settlement, the manufacturers have agreed to develop low NO_x rebuild kits for a range of popular engine models manufactured between 1993 and 1998. These kits will essentially bring the NO_x levels of affected engines down by about 25 percent. The kit is to be available at no extra cost to rebuilders and owners, and all engines within the model year range that are selected by manufacturers must be rebuilt using this kit. Such kits are expected to be available in the marketplace shortly.

As noted, only the two regulatory programs are expected to have a significant influence on rebuild and retrofit. The U.S. EPA is considering other rebuild and retrofit requirements for heavy-duty diesels but no actions are expected in the near future.

Recommendations for Australia

The need for control strategies to address heavy-duty is very much dependent on the rates of mal-performance and tampering found in Australia. Anecdotal evidence from industry sources varies, and a survey would be required to obtain an objective estimation.

If these rates are quite low, then the programs may not be cost effective and will lead to a situation as in Europe, where almost no one fails the inspection for emissions. At present, the only type of control program in existence is based on smoke emissions. Such programs to control smoke emissions have popular public support, and analysis by California has shown a random roadside program (where potential failures are visually identified and tested)can be very cost effective and result in reductions to HC and PM emissions , in addition to being a deterrent to tampering. This type of program may be the only one suitable for Australia, since Australia has had a smoke emissions standard that engines must meet since the 1970s.

Retrofit of technology to reduce emissions has focused primarily on reducing particulate emissions, and a number of commercial products are available for the European market that are suitable for Australian engines imported from Europe. Similar products are being developed for some US and Japanese engines, especially those fitted to buses. While the performance of these products is good, costs are still very high and most sales have been to Metropolitan bus operators. It is not clear that such devices are cost effective for Australia.

Upgrade at engine rebuild to a lower emissions specification is also possible, but a rebuild kit must be developed with assistance from the engine manufacturer. Such kits are available for some engines, but certainly not for all engines. As a result, it will not be possible to impose a regulatory requirement to upgrade all engines at rebuild. A market based approach offering incentives to manufacturers may result in such kits becoming available for at least some of the more popular high sales volume engine lines in Australia.

1 INTRODUCTION

The National Environmental Protection Council (NEPC) is undertaking a critical examination and assessment of emission from diesel engine powered vehicles in Australia. Diesel engines are extensively used in heavy-duty trucks and buses, but have little penetration in the light-duty vehicle fleet. For a number of reasons unique to heavy-duty vehicles, the emissions from diesel engines used in this application have been traditionally quantified using an engine dynamometer based test. The correlation of measured emissions between such tests and vehicle-based tests conducted on a chassis dynamometer has been of much interest recently, since more focus has been placed on the in-use (as opposed to certification) emissions of diesel-powered vehicles.

The interest in the in-use emissions of heavy-duty diesels has grown as light-duty vehicles have been controlled to increasingly stringent standards. Heavy-duty diesel vehicles are now a significant contributor to the total NO_x and combustion derived particulate matter (PM) inventory in Australia. In-use emissions of diesels have also been historically assumed to be near certification levels, but recent testing has shown that this assumption may not be valid, and in-use deterioration may be significant. As a result, programs are being developed in OECD countries to control in-use heavy-duty diesel vehicle emissions, and to further reduce their emissions by retrofitting advanced emission control technologies to older vehicles in service.

1.1 OBJECTIVES

The NEPC has issued two projects to study these issues. The first (NEPC Project 5) is to conduct a critical examination of the literature and on-going efforts to establish a correlation between measured emissions on a chassis dynamometer and on an engine dynamometer. The second (NEPC Project 6) requires an examination of the emissions deterioration that takes place under in-service conditions. The project also requires an examination of regulatory and non-regulatory programs to maintain original emissions performance over the useful life, as well as reducing in-service emissions though retrofit of advanced emission control technology.

1.2 REPORT OUTLINE

Projects 5 and 6 rely on a common set of data that includes emissions from in-use vehicle engines measured using both chassis based and engine based tests. The analyses for the two projects also rely on a common understanding of test cycles and certification levels. As a result, the reports for the two projects are combined, with Section 2 providing the overview of engine based test cycles and certification standards, while Section 3 detailing the chassis based test procedures and their development.

Sections 4 and 5 address the issues related to Project 5, and provide details on emission correlation issues. Section 5 addresses these issues in the Australian context, and discusses the implications of testing vehicles encompassing a wide range of sizes and engine output, country of origin, certification standards, age and condition.

Sections 6, 7, 8 address issues raised in Project 6. Section 6 examines the literature on deterioration of diesel emissions under in-service conditions. Though the data is limited, there are some conclusions of interest to Australia. Section 7 provides an overview of control programs both in terms of maintaining original emission levels and in terms of retrofit of technologies. An evaluation of the emission reduction benefits, cost-effectiveness and practicality of these control programs for Australia is provided in Section 8.

2 EMISSION STANDARDS AND TEST PROCEDURES FOR HEAVY-DUTY DIESEL ENGINES

2.1 OVERVIEW

Although Australia had only a smoke opacity standard for heavy-duty diesel engines until 1996, engines imported into Australia have generally employed most of the technological improvements brought about as a result of emission standards applicable in the country of manufacture. While these engines need not necessarily be calibrated to meet the same standards as engines sold in Australia, there is the potential that some of the diesel engines imported into Australia have largely similar emission characteristics as the same model sold in the country of origin. However, many engines imported from Japan may have been certified to UN based ECE requirements.

Since 1995 (for new design engines) and 1996 for all engines, the relevant Australian Design Rule, ADR 70, has referenced the European ECE R49/02 standards for compression ignition engines as the appropriate regulation for heavy-duty diesel engines (HDDE) sold in Australia. However, the ADR also allows engines to be certified to two alternative standards for heavy-duty engines:

- The USA standards applicable to either 1991 to 1993 heavy-duty engines or 1994 and later heavy-duty engines;
- The 1994 Japanese exhaust emission standards for heavy-duty vehicles.

Hence, it is likely that engines sourced from Europe, Japan and the USA (which constitute the overwhelming majority of all engines sold in Australia) since 1996 are certified to standards in their country of origin, largely because development of a special Australian version would not be generally cost-effective.

The three standards that ADR 70 refers to are quite different in stringency, and different test procedures are used to certify these engines as well, so that the numerical emission standards are not directly comparable. This section details the historical standards and certification test procedures used to serve as a reference or a benchmark for the analysis. Standards and test procedures are detailed below.

Heavy-duty vehicle certification emissions testing is performed on an engine rather than vehicle specific basis due to several issues unique to the heavy-duty vehicle sector. For example, the same heavy-duty engine can be used across a number of vehicle classes of widely differing weight characteristics. In addition, the same engine can be coupled with several different drivetrains. In fact, the same vehicle may be offered with several independent engine and drivetrain options. Thus, the number of vehicle/engine/drivetrain combinations, each of which would have to demonstrate compliance individually if emissions certification was vehicle specific, is substantially greater in the heavy-duty sector than is the case in the light duty sector.

Compounding this complexity are several other issues. Heavy-duty vehicle manufacturers often use engines manufactured by others. Therefore, targeting responsible parties for compliance purposes on a vehicle specific basis would necessarily involve the resolution of applicable cross manufacturer issues. Vehicle specific test equipment demands are also of concern. Chassis dynamometer capabilities required to test the full range of heavy-duty vehicles are substantially more demanding (and expensive) than those required for light duty vehicle testing. Heavy-duty vehicles can have inertial weights ranging from 3,000 to 40,000 kg or more, whereas light duty vehicle inertial weights of 1,000 to 5,000 kg are typical.

A 4,000 kg dynamometer inertia capacity is sufficient to test almost any light duty vehicle produced. Even in use vehicle emissions inspection and maintenance programs have moved to dynamometer-based inspections in the U.S. given the relative cost effectiveness of light duty test equipment. Conversely, there remain only a handful of facilities in the U.S. with chassis dynamometers capable of testing at heavy-duty vehicle inertial weights of even 10,000 kg. As a result, certification testing in all OECD countries is currently engine based.

2.2 U.S. HEAVY DUTY DIESEL ENGINE EMISSIONS STANDARDS

The U.S. EPA sets emission standards for new non-California heavy-duty diesel (HDD) engines. The California Air Resources Board (ARB) is responsible for setting emission standards for HDD engines that are sold as new in California. Federally certified heavy-duty diesel vehicles (HDDV) may be registered in California as a result of relocation by the vehicle's owner or as a result of sale of the vehicle to an in-state operator.

This section discusses both U.S. Federal and California emission certification standards and procedures for new heavy-duty diesel engines. All of the historical standards, as well as current and future standards, are presented, since some HDD engines typically remain in service considerably longer than light duty engines and many older HDD engines are still in service. In fact, HDD engines are designed to be rebuilt and are typically rebuilt more than once throughout their lives.

2.2.1 *U.S. Federal HDD Emission Standards*

The U.S. EPA has set standards for emissions from heavy-duty diesel engines since 1974. Emission standards for hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate have been periodically revised during the intervening years, and the emission test procedure itself was changed in 1985. The U.S. EPA has recently proposed emission standards for 2004 and subsequent model year HDD engines, and is in the process of setting standards for post-2007 engines. U.S. standards are expressed in g/bhp-hr, and to convert to the European g/kWh basis, they should be multiplied by 1.341. The U.S. standards cover diesel engines used in all vehicles over 8,500 lb GVW, or 3.86 tonnes GVW.

Table 2-1 lists the emission standards for new Federal heavy-duty diesel engines.1 All of the certification tests are performed on an engine dynamometer, but prior to 1985 the test consisted of measuring the emissions at thirteen steady-state test points. Since 1985, the test procedure has been a transient procedure with starts, stops and speed/load changes. The transient test is more representative of actual engine operating conditions than the steady-state test procedure, and is discussed in Section 2.6.

The proposed 2004 standards2 will allow the manufacturers to meet standards of 0.5/2.0 g/bhp-hr or 0.67/2.68 g/kWh for HC/NO_x respectively and a standard of 2.4 HC+ NO_x g/bhp-hr or 3.22 g/kWh. These standards are based on the existing transient test used since 1984. However, the U.S. EPA recognises that the existing test does not cover a range of in-use operating conditions. Hence, the U.S. EPA has proposed reintroducing the 13-mode test, as modified for the European stationary test cycle described below (not all aspects of the U.S. EPA proposed cycle may be identical to the ESC). The EPA has also proposed that it be allowed to select three additional test points in the emission control range of the engine to assure itself that emissions do not peak outside the test envelope, and has introduced a maximum allowable emissions limit (MAEL) based on these three test points. Separately, the U.S. EPA has also proposed Not-to-Exceed emission limits that involves testing under any feasible driving condition including-cold start, and is intended to ensure that no defeat device is used to allow high emissions in some part of the operating range.

Table 2-1: US Federal Exhaust Emission Standards for Heavy Duty Diesel Engines (g/kWh)

Model Year[1]	Hydrocarbons	Carbon Monoxide	Oxides of Nitrogen	HC + NO_x	Particulates	Smoke Opacity	
1970-1973	--	--	--	--	--	Accel.	40%
						Lug	20%
1974-1978	--	53.64	--	21.46	--	Accel.	20%
						Lug	15%
						Peak	50%
1979-1983	2.01	33.53	--	13.41	--	Same	
	--	33.53	--	6.71	--		
1984[2]	1.74	20.79	14.35	--	--	Same	
	0.67	20.79	12.07	--	--		
1985-1987	1.74	20.79	14.35	--	--	Same	
1988-1990	1.74	20.79	8.05	--	--	Same	
1991-1993	1.74	20.79	6.71	--	0.34[3]	Same	
1994-1997	1.74	20.79	6.71	--	0.14	Same	
1998-2003	1.74	20.79	5.36	--	0.14	Same	
2004 and Subsequent	0.67	20.79	2.68	3.22	0.14	Same	

[1] The steady-state procedures were used through 1984 and the transient procedure has been used since 1985.

[2] Manufacturers had the option of using the 1983 procedure and standards, or standards of 1.74 HC, 20.78 CO and 14.35 NO_x on the transient procedure or standards of 0.67 HC, 20.78 CO and 12.07 NO_x on the steady-state procedures.

[3] See text for discussion of urban bus emission standards.

Source: US.40 Code of Federal Regulations (CFR) Part 86, Appendix 1, Section (f)

Note: Original standards expressed in gm/bhp-hr

The EPA has exempted the low RPM, low torque range and a part of the high RPM/low torque range as part of the operating range where the "Not-to-Exceed" (NTE) limits will be placed. The ranges are shown schematically in Figure 2-1 and Figure 2-2 for high RPM and low RPM engines.

Finally, the U.S. EPA has also proposed a rapid acceleration test that requires moving from light load to full throttle acceleration at six different RPM level. Hence, the proposed changes for 2004 and later years involve a range of new certification tests and procedures.

The Table shows that given the longevity of heavy-duty diesel engines, it is to be expected that the in-use heavy-duty engines in Australia imported from the U.S. could have been certified to any of seven emissions standards. It also shows that emission standards for CO and combined HC and NOx were tightened considerably in steps between 1973 and 1984. The combined HC and NO_x standards were discontinued in 1984. Particulate standards, introduced in 1988, were reduced in 1991, and have been reduced again in 1994.

The particulate standards may be met by averaging across all engine families (except those used in urban buses) that a manufacturer markets within each useful life category. Since 1974 new heavy-duty diesel engines sold in the U.S. have not been allowed to exceed 20 percent average opacity during acceleration, 15 percent average opacity during loaded lug down, and 50 percent peak opacity during acceleration.

Heavy-duty diesel engines are required to meet the emission standards in Table 2-1 for their designated useful lives. The emissions from urban buses are of more concern to human health than are emissions from other HDDV because the general public is more directly exposed to urban bus emissions than to the emissions from other HDDV. Particulate matter in diesel exhaust is the pollutant of most concern, as certain carcinogenic materials are known to be carried on the particulate. Therefore, particulate matter (PM) emission standards for urban buses were more stringent than those for other HDDV, at least in the interval 1991 to 1993. Beginning in 1991, urban buses were required to meet a 0.1 g/bhp-hr or 0.134 g/kWh particulate standard, while other HDDV were required to meet the 0.1 standard only by 1994. The PM standards for buses are set at 0.07 g/bhp-hr (0.994 g/kWh) for 1994-95 and at 0.05 g/BHP-hr (0.067 g/kWh) for 1996 and later years.

The emission standards that have been discussed are applicable only to new HDD engines, but since HDD engines are typically rebuilt one or more times, it has been suggested by regulators that rebuilt HDD engines could be modified in a manner that would reduce emissions from in-use HDD engines. To date, EPA has promulgated a requirement only for the rebuild or a retrofit for 1993 and earlier urban buses. Operators of urban bus fleets in metropolitan areas with 1980 populations of 750,000 or more are required to choose between two options. The first sets PM emission requirements for each engine that is rebuilt or replaced. The second option is a fleet average PM standard that requires an operator to meet specified annual target levels for all pre-1994 buses in the covered fleet. Although the standards are engine specific, most pre-1988 bus engines are required to meet a PM level of 0.3 or 0.5 g/BHP-hr (0.4 to 0.67 g/kWh), depending on technology feasibility, after rebuilding. Rebuild requirements for all other heavy-duty diesel trucks are under study, and there are regional and voluntary programs that are discussed in Section 8.

2.2.2 *California HDD Emissions Standards*

The Air Resources Board (ARB) is responsible for setting heavy-duty diesel engine emission standards for engines that are sold in of California. Opacity limits for smoke were initiated in 1968, and standards for HC, CO, and NO_x were introduced in the 1973 model year.

Table 2-2 lists the emission standards for new heavy-duty diesel engines sold in California.

Figure 2-1: Proposed NTE Zone for Heavy-Duty Diesel Engines – C Speed < 2400 rpm

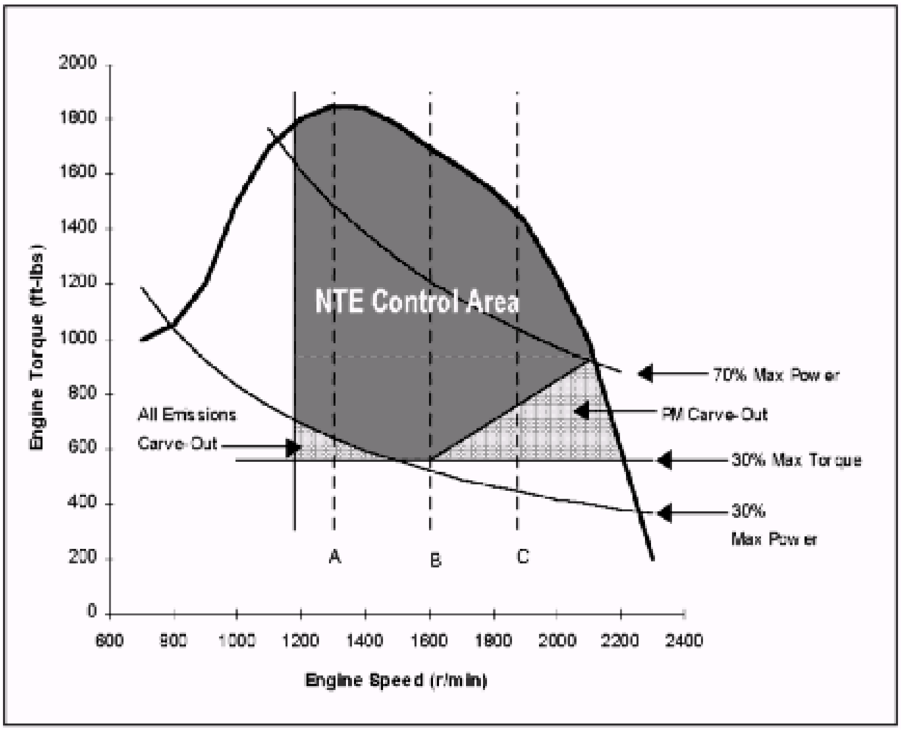


Figure 2-2: Proposed NTE Zone for Heavy-Duty Diesel Engines – C Speed > 2400 rpm

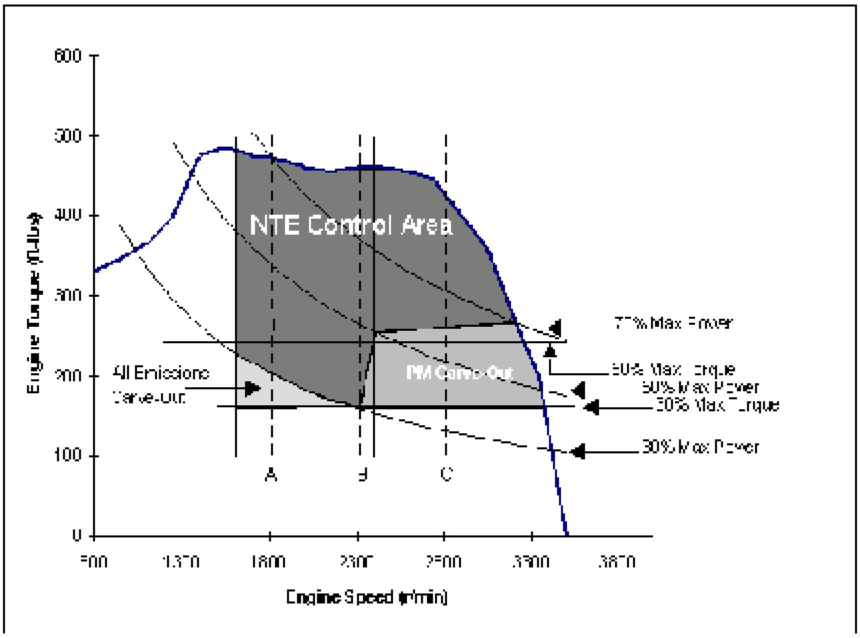


Table 2-2: California Exhaust Emission Standards for Heavy Duty Diesel Engines (g/Kwh)

Model Year (1)	Total Hydrocarbons	Non Methane Hycrocarbons (2)	Carbon Monoxide	Oxides of Nitrogen	HC + NOx (3)	Particulates
1973-1974	--	--	53.64	--	21.46	--
1975-1976	--	--	40.23	--	13.41	--
1977-1979	--	--	33.53	--	6.71	--
	1.34	--	33.53	10.06	--	--
1982-1983	1.34	--	33.53	--	8.05	--
	--	--	33.53	--	6.71	--
1984	0.67	--	33.53	--	6.03	--
1985-1987	1.74	--	20.79	6.84	--	--
1988-1989	1.74	--	20.79	8.05	--	0.80
1990	1.74	1.61	20.79	8.05	--	0.80
1991-1993	1.74	1.61	20.79	6.71	--	0.34 (4)
1994-1997	1.74	1.61	20.79	6.71	--	0.13
1998 and Subsequent	Per U.S. Federal Standards					

[1] The steady-state procedure was used through 1984 and the transient procedure has been used sine 1985.
[2] Manufacturers may choose to certify to the total HC or the non-methane HC standards.
[3] Manufacturers had the option of certifying to separate HC and NO_x standards or to a combined HC + NO_x standard in 1977-1979.
[4] See text for discussion of urban bus emission standards.
Note: Original standards expressed in gm/bhp-hr

The exhaust emissions are measured using the same test procedure that EPA uses, the only difference being that manufacturers had the option of using the transient test procedure beginning in 1983 in California. The Table shows that the California standards were generally a year or more ahead of the Federal standards, but that the Federal and California standards for all pollutants are essentially the same after 1988, and identical after 1998.

The ARB was also directed by the legislature to consider emission control technology, cleaner burning diesel fuels, and alternative fuels as methods that may be used to meet any new emission standards. One technology that has the potential for reduced emissions at relatively low cost is positive crankcase ventilation (PCV). ARB required that all transit bus engines have positive crankcase ventilation systems beginning in 1996. In addition, ARB has adopted the Federal transit bus standards for particulate and NO_x emissions.

ARB has responded to the legislative requirements for low emission vehicles by adopting a program that generates emission reduction credits for low emission retrofits of existing vehicles or the purchase of low emission transit buses (ARB:1996). Hence, market mechanisms are being employed to spur the sales of low emission buses and to rebuild engines to lower emission standards. “Low emission” engines can be certified to a range of “credit standards” which are at least 30 percent lower than the ceiling standard. The ceiling standard is the standard for which the engine was originally certified to when first placed in service, or a standard indicated by ARB for pollutants where no standard existed at the time the engine was placed in service. For example, a retrofit of 1987 Heavy Duty Diesel Engine originally certified to a 6.0 g/BHP-hr (8.04 g/kWh) NO_x standard would have to be at 4.0 g/BHP-hr (5.36 g/kWh) or lower to obtain emission credits. California has specified a credit certification procedure and a calculation procedure to derive the amount of credit generated by a single retrofit or purchase of a low emission engine.

California HDT customers would not be required to use engines that meet these low emissions standards, but would be encouraged to do so by the existence of NO_x emission credit programs that would be administered by the air quality districts. Bus manufacturers have expressed concern that few customers will be willing to pay the premium for low emission bus engines that manufacturers must charge for low sales volume engines, and consequently, little benefit may be gained from the standards.

2.3 EUROPEAN REGULATIONS

The ECE regulations (www.dieselnet.com/standards.html) have been in force since 1982, and the original regulation is referred to as the ECE R49 standard. Europe has always utilised the 13-mode test, a steady-state test conducted on an engine dynamometer, which is very similar to the U.S. 13-mode test utilised for certification before 1984. The 13-mode test continues to be used to this day. The standard (officially) between 1982 and 1990 was 18.0 g/kWh for NO_x, which was significantly higher than any U.S. standards in the 1980s.

Although the standards were modified officially in 1990 as part of the 88/77/EEC regulation, German manufacturers had voluntarily undertaken to keep emission levels at least 20 percent below ECE R49 from 1987, which compared closely to the 88/77/EEC requirements. It is not clear if other non-German manufacturers participated in the voluntary program. The so-called Euro I and Euro II standards were introduced in calendar year 1992 and 1996 respectively, with the Euro III and Euro IV standards planned for 2000 and 2005, respectively. As these standards come into force in October of the years mentioned, they really apply to model years 1993, 1997, 2001 and 2006. There is also a Euro V standard for 2008 and beyond that has been recently promulgated.

In addition to the numerical change in emission standards, the ECE R-49 13 mode test cycle (also described in Section 2.5 and 2.6) is to be changed with the Euro III and later standards. The new procedure requires two test cycles, one a steady-state cycle called the European Stationary Cycle (ESC), and the second, a transient test called the European Transient Cycle (ETC). These new tests have resulted in standards being more stringent than implied by the numerical value reduction relative to the Euro II standard. In addition, the Euro III and later standards also require compliance with a smoke test that involves a transient short cycle, called the European Load Response cycle. Maximum smoke opacity on this cycle is restricted to 0.7/m for Euro III and 0.5/m for Euro IV and V standards.

Table 2-3 shows the European standards through the proposed Euro IV standard for both steady state and transient (for Euro III and later) tests.

Table 2-3: European Heavy-Duty Engine Emission Standards (g/kWh)

(a) Steady State Cycle

Regulation	HC	CO	NO_x	PM
ECE R49 (15-4-1982)	3.5	14	18	None
88/77/EEC (1-10-90)*	2.4	11.2	14.4	None
				0.61(<85 kw)
Euro I (1-10-93)	1.1	4.5	8	0.36 (>85 kw)
Euro II (1-10-96)	1.1	4	7	0.15
Euro III (1-10-00)**	0.66	2.1	5	0.10(0.13)a/
Euro IV (1-10-05)	0.46	1.5	3.5	0.02
Euro V	0.46	1.5	2	0.02

(b) Transient Test

Regulation	HC	CO	NO_x	PM
Euro III	0.78	5.45	5	0.16(0.21)a/
Euro IV	0.55	4	3.5	0.03
Euro V	0.55	4	2	0.03

* Voluntary compliance by German manufacturers since 1987.
** Special standards for "environmentally friendly vehicles" of 0.25/1.5/2.0/0.02.
a/ For high speed engines with cylinder displacement of <0.75 dm^3.

The Euro II standard has a NO_x stringency that is approximately similar to the U.S. 1994-1997 standard, but the particulate standards are not comparable due to the differences in test procedure. The Euro III standard is comparable to the U.S. 1988-2003 standard in stringency for the transient test, while the Euro IV standards are somewhat less stringent for NO_x but more stringent for PM relative to the U.S. 2004 standard. Note that both the Euro II and Euro III standards have less stringent PM standards for small diesel engines. The U.S. is planning to implement a 2007+ standard that may be equal to the Euro V standard, in the interest of harmonisation.

2.4 JAPANESE STANDARDS

The Japanese standards for heavy-duty diesel engines are also based on a 13-mode test cycle, although the modes are defined differently relative to the ECE-R49 test. However, Japanese standards applicable for the last ten years are quite similar to the Euro II standard for NO_x, but are considerably less stringent for PM in numerical terms (SAE:1973).

Since model year 1999, the NO_x and PM standards have been reduced considerably, with the NO_x standard being somewhat lower numerically than Euro II and the PM standard being somewhat higher. However, the Japanese 13-mode cycle has a considerably higher weighting of the idle mode (41 percent) so that the numerical values are not readily comparable, especially for PM. It may be that the stringency adjusted for test cycle differences make the current standard similar in stringency for NO_x and PM to Euro III, since the idle mode contributes to PM but not to NO_x. The Japanese standards are shown in Table 2-4. Note the special exemption for low sales volume engines, as well as the interpretation of standards as a production mean. It should also be noted that Japan is considering reducing standards for all pollutants by 50 percent for model year 2007 or 2008.

Table 2-4: Japanese Standards For Heavy –Duty Diesel Vehicles (g/kWh, maximum/mean)

	Effective Date	
Emission	**12/89-9/98***	**10/98+**
HC	3.8/2.9	3.8/2.9
CO	9.2/7.4	9.2/7.4
NOx	DI 7.80/6.00 IDI 6.80/5.00	5.80/4.50
PM	0.96/0.70	0.49/0.25

The maximum standard has to be met as a type approval limit if sales are less than 2000/yr.

The mean has to be met as a type approval limit and as a production average.

Standards prior to this model year (1999) differed between direct injection (DI) and indirect injection (IDI) diesels. Typically, IDI diesels were used only in relatively small vehicles, (3.5 to 8 tons GVW) but since these vehicles are popular in Australia, it may be an issue for consideration.

2.5 STEADY STATE CERTIFICATION TEST

Of all test cycles, steady state modal cycles represent the most straightforward and simplest approach to representing heavy-duty vehicle or engine emissions performance. While many such cycles have been developed over the years, they all can be described generally as a series of steady state operating modes (defined by specific engine speed and load values) at which emissions are measured. Aggregate cycle emissions are characterised by applying specific modal weighting factors to the emissions measured over component operating modes.

Among the first of the steady state modal cycles to be formalised is the J1003 Diesel Engine Emission Measurement Procedure, more commonly known as the 13-Mode Cycle, adopted by the Society of Automotive Engineers (SAE:1973). The specific J1003 cycle modes and weighting factors are presented in Table 2-5.

Although J1003 is an engine-based cycle, its steady state characteristics make it adaptable to a vehicle-based test. Moreover, the design theory of the J1003 cycle has been extended to a substantial number related cycles over the years. Its closest relative is the European ECE R49 test cycle, which has been used for engine certification testing in Europe since the late 1980's.

Table 2-5: SAE J1003 and ECE R49 Test Cycles

Mode	Engine Speed	Fractional Load (%, ±2%)	SAE J1003 Weights	ECE R49 Weights
1	Idle	0	0.20/3	0.25/3
2	Peak Torque*	2	0.08	0.08
3		25	0.08	0.08
4		50	0.08	0.08
5		75	0.08	0.08
6		100	0.08	0.25
7	Idle	0	0.20/3	0.25/3
8	Rated	100	0.08	0.1
9		75	0.08	0.02
10		50	0.08	0.02
11		25	0.08	0.02
12		2	0.08	0.02
13	Idle	0	0.20/3	0.25/3

* Unless peak torque speed is less than 60 percent of rated speed, in which case modes 2 through 6 should be performed at 60 percent of rated speed.

Although the Euro III standards will substitute a realistic transient based cycle in the near future, the ECE R49 cycle continues to be the official European test cycle for heavy-duty diesel vehicle certification testing to this day.

Finally, even though the era of on road emissions testing using the J1003 cycle is drawing to a close, the cycle will continue to serve as the basis for off road engine testing through the International Standards Organisation (ISO). The ISO 8178 standard covers emissions from a wide range of off road engine applications and relies on the same 13 operational modes originally established for the SAE J1003 standard (only the specific weighting factors applied to each mode to determine aggregate emissions vary across specific off road applications).

The only difference between the J1003 and ECE R49 cycles is the mode specific weighting factors used to determine aggregate cycle emissions as presented in Table 2-5. The ECE R49 test reflects a weighted average load of about 50 percent of rated load (and a weighted average speed of about 52 percent of rated speed). While the J1003 cycle reflects a significantly lower weighted average load of about 40 percent of rated load (but at a significantly higher weighted average speed of about 64 percent of rated speed). As a result, PM and NOx emissions measured over the aggregate ECE R49 cycle tend to be higher than emissions measured over the aggregate J1003 cycle.

The Japanese 6- and 13-Mode Cycles are also derivatives of the J1003 cycle, but both apply to vehicle specific, rather than engine specific emissions. Specific cycle modes and/or weighting factors for both the Japanese 6-Mode (shown in Table 2-7) and Japanese 13-Mode Cycles differ for gasoline and diesel vehicles, with the primary intent being to accurately reflect urban driving conditions in Japan. The Japanese 13-mode uses a different set of loads and speeds than the ECE

R49, with the engine exercised only up to 80 percent of rated speed. The highest power rating on the test is 95 percent of peak torque at 60 percent of rated RPM. The high weighting of idle and the relatively low loads and speeds are to represent the low speed driving conditions in Japan. The modes and weights are shown in Tables 2-6 and 2-7.

Table 2-6: Other 13-Mode Cycles

	Japanese 13-Mode			ESC		
Mode No.	**Speed**	**Load**	**Weight**	**Speed***	**Load**	**Weight**
1	Idle	0	0.205	Idle	0	0.15
2	40	20	0.037	A	100	0.08
3	40	40	0.027	B	50	0.1
4	Idle	0	0.205	B	75	0.1
5	60	20	0.029	A	50	0.05
6	60	40	0.064	A	75	0.05
7	80	40	0.014	A	25	0.05
8	80	60	0.032	B	100	0.09
9	60	60	0.077	B	25	0.1
10	60	80	0.055	C	100	0.08
11	60	95	0.049	C	25	0.05
12	80	80	0.037	C	75	0.05
13	60	5	0.142	C	50	0.05

Note: Speed and load as percent of rated speed and maximum torque.
* Speeds A, B, and C are defined on the basis of the torque curve and tend to be speeds spread around the peak torque RPM.

Table 2-7: Japanese 6-Mode Diesel Test Cycle

Mode	Fractional Speed (% of Rated)	Fractional Load (% of Rated)	Weight
1	0	0	0.355
2	40	100	0.071
3	40	25	0.059
4	60	100	0.107
5	60	25	0.122
6	80	75	0.286

The new European stationary cycle (ESC) has a more complex definition of modes that accounts for the torque characteristics of the particular engines under test. N_{HI} is defined as the highest engine speed (above rated speed) at which the engine can produce 70 percent of rated power, while N_{LO} is the lowest engine speed at which the engine can produce 50 percent of rated power.

Speeds A, B and C are defined as:

$$A = N_{LO} + 0.25\,(N_{HI} - N_{LO})$$
$$B = N_{LO} + 0.50\,(N_{HI} - N_{LO})$$
$$C = N_{LO} + 0.75\,(N_{HI} - N_{LO})$$

The resultant modes are also shown in Table 2-6. For engines with little governor ‘droop’, N_{HI} is very close to rated RPM. As noted, the U.S. EPA has proposed adopting a test very similar to the ESC, but with slightly different technical requirements.

Other steady state modal cycles have been developed by researchers with the sole intent of allowing the correlation of vehicle based emissions measurements with their transient engine based certification counterparts. Two such cycles are an 8-mode vehicle based cycle developed by Cartellieri et al. In 1989 and a second 6-mode engine based cycle developed by Montgomery et al. At the University of Wisconsin Madison in 1996 (Hoppie:1997). Table 2-8 presents the Cartillieri cycle.

Table 2-8: Cartellieri 8-Mode Test Cycle

Mode	Fractional Speed (% of Rated)	Fractional Load (% of Rated)	Weight
1	34	0	0.417
2	41	25	0.075
3	47	63	0.035
4	55	84	0.04
5	100	18	0.1
6	97	40	0.124
7	97	69	0.122
8	93	95	0.087

Although it is claimed that this cycle correlates well with transient cycles, caution should be employed for several reasons. The speed and load combinations included in the heavy-duty engine certification tests are extensive. The diesel certification cycle is more heavily weighted to high speed loads and may be more amenable to speed/load grouping, but even so the observed load range over a restricted high speed band is fairly “continuous.” Most importantly, as discussed below, the heavy-duty certification tests for diesel engines are highly transient in nature, with frequent, rapid accelerations from idle to rated or narrated speed. No steady state modal tests can capture the emissions impact of such transients, events that have been shown (as discussed below) to be critically important to measured emission levels [1].

2.6 TRANSIENT TESTS

The engine based heavy-duty emissions certification transient test cycle is expressed in terms of normalised engine speed and torque. As a result, all engines are tested over a driving cycle theoretically tailored not only to their specific performance levels, but also to equivalent relative energy demands. Figures 2-3(a) to (c) illustrate the U.S. Federal engine certification test cycle specifications for diesel engines. The Figure consists of three subfigures (labelled a b, and c), the first two of which present the continuous speed and torque traces that define the certification cycle and the third of which provides an illustration of the range of covered power settings.

[1] Some research on modal cycles has demonstrated a reasonable comparison between modal-based and transient cycle NO_x emission rates for heavy-duty vehicles. However, researchers at West Virginia University have recently demonstrated that there is indeed an underestimate of NO_x if acceleration events are not reflected in NO_x emission rates. Regardless, the emission rates of other emission species, especially particulate matter, are quite dependent on acceleration events.

The Federal certification cycle is actually defined in discrete one second intervals. In subfigures (a) and (b), these one second intervals have simply been linearly connected to produce a continuous trace (as is common practice for all driving cycle development), while subfigures (c) present only the discrete one second power settings which actually define the certification cycle. Therefore, each of the power setting markers depicted in subfigure (c) represents an equal time period of one second. The total cycle time spent at any restricted range of power settings is indicated by the clustering of discrete one second markers.

The EPA engine transient cycle was derived from a detailed study of actual truck driving habits using instrumented trucks operating in New York and Los Angeles. The data collected was analysed statistically, and a cycle was derived that captures the most common driving characteristics. The U.S. transient cycle has three segments:

- the New York city cycle with an average speed of 11.74 km / hr;
- the Los Angeles non-freeway cycle with a speed of 27.0 km / hr;
- the Los Angeles freeway cycle with a speed 75.34 km / hr.

Engine manufacturers have complained that the statistical analysis combined data from dissimilar vehicles and some of the transients in the cycle cannot be observed in real life.

Figure 2-4(a) and (b) show the density plots for the new European Transient Cycle (ETC) versus the U.S. cycle (TUV:1995), and it seems that this cycle has a wider representation of loads and engine speeds than the U.S. Transient Cycle. The ETC also has three segments:

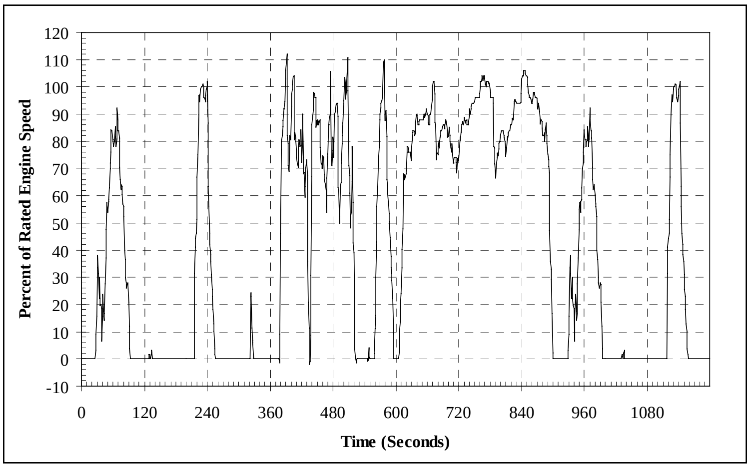
- a city segment with an average speed of 50 km / hr, and frequent stops;
- a rural driving segment with hard accelerations and average speeds of 72 km / hr;
- a highway segment with an average speed of 88 km / hr.

Broadly speaking, the ETC is quite similar in concept to the U.S. Transient Cycle. Recent testing has shown that emission results from the two tests are correlated, and the wider speed / load ranges encountered in the ETC typically increase HC, CO and PM emission relative to those measured on the U.S. cycle.

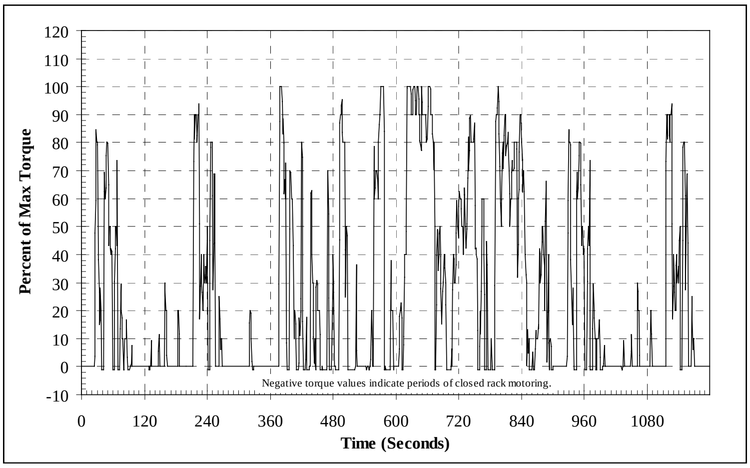
Because the certification cycles are defined on the basis of maximum test engine speed and torque, a larger engine will be “exercised” to the same extent over the certification test cycle as a smaller engine (i.e., the load factor for the certification test is constant across test engines). However, both engines may be used in vehicles with similar in-use duty cycles.

Figure 2-3: Federal Test Procedure for Heavy-Duty Diesel Engines

a)



b)



c)

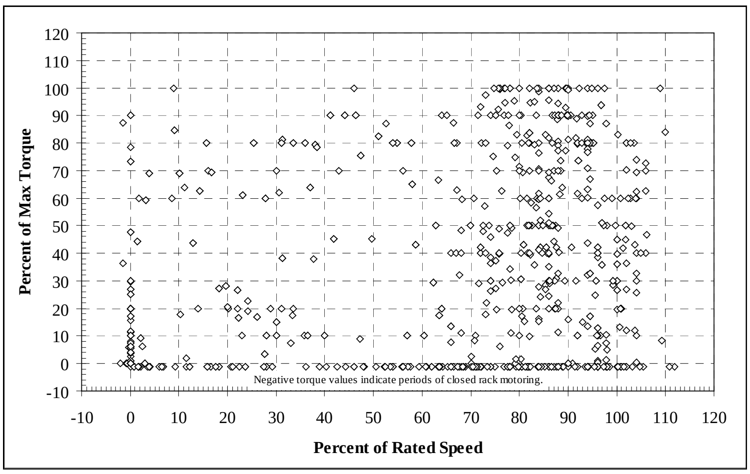
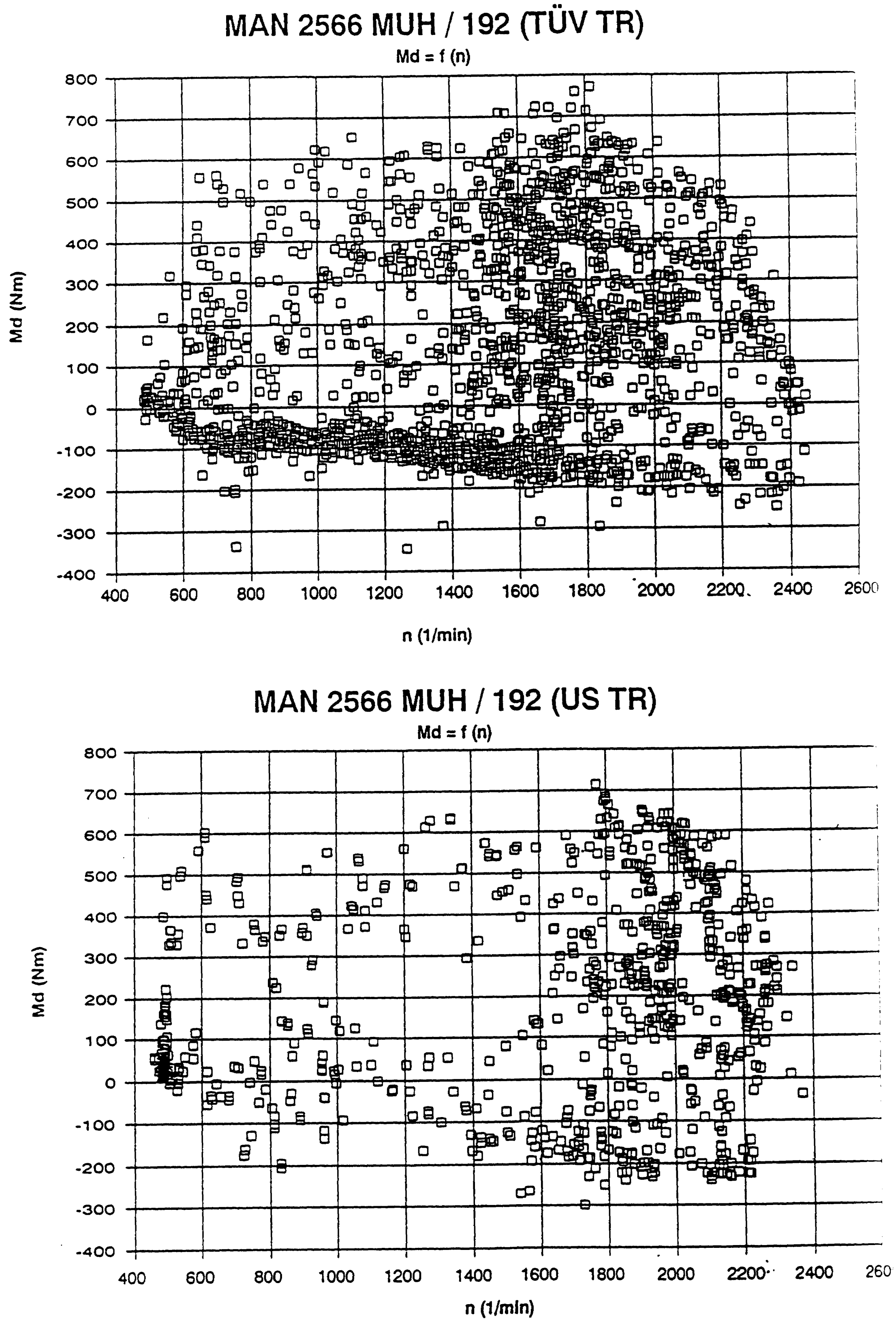


Figure 2-4: Comparison of US and European Transient Cycles



Source: TUV (1995)

In such a case, the smaller engine may indeed experience in-use operational characteristics similar to those of the certification test, while the larger engine typically operates at substantially lower power demands (and, all other factors being equal, at emission rates lower than implied by the engine certification test). In contrast, light duty vehicles are certified over a transient driving cycle that is the same for all test vehicles. Overpowered vehicles will work less over the test cycle than "underpowered" vehicles and, as long as the cycle itself is representative of in-use operations, the real world emission rates of the two engines (ignoring such issues as deterioration, mal-maintenance, and tampering) will be described in a proper relative sense.

Further confounding the translation of engine specific to vehicle specific emission rates is the need to consider such issues as gearing ratios and power losses between the vehicle engine and its drive wheels. Engine specific emission rates, unaffected by drivetrain issues, are expressed in mass per unit of engine work (typically grams per brake horsepower-hour or per kWh). A vehicle specific conversion factor which considers drivetrain impacts in expressing engine work required per unit distance travelled (typically brake horsepower-hour or kWh per mile) can theoretically be developed to generate the mass per unit distance (typically grams per mile) emission rate commonly used to assess vehicle specific emissions performance. However, while such a conversion factor can be developed from brake specific fuel consumption (BSFC), fuel density, and fuel economy measurements, research has shown (not surprisingly) that two of these vehicles related parameters vary with operating mode. The issues are discussed in Section 4 of this report.

3 CHASSIS TEST CYCLES

3.1 OVERVIEW

Testing of heavy-duty trucks, as opposed to engines, has been very limited around the world, largely because chassis dynamometers capable of handing trucks in excess of 5,000 kg loaded weight are quite rare. For example, even in the U.S. where there has been truck testing conducted for over 30 years, there are currently only four facilities capable of conducting transient cycle tests on trucks with an inertia weight of over 8,000 kg. The number in Europe is similarly small, and only two of the facilities have the capability of conducting full scale transient tests. Japan has only one such facility and there are none in Australia. As a result, the test cycles and test procedures are in a state of infancy relative to the highly developed test procedures for light-duty vehicles, whose inertia weights are typically in the 1,000 to 2,000 kg range. In this context, the same issues are not present for light-duty vehicles since the certification test is specified as a chassis dynamometer test, and the certification test can be performed by numerous laboratories in Australia. Moreover, the test is identical for light-duty diesel and gasoline vehicles, although diesels must also certify to a smoke test in EU countries.

There has been virtually no interest in the U.S. in replicating the 13-mode engine steady state test on a chassis dynamometer in the U.S. since it was known since the late 1970s that the test would not be used for certification after 1984. Hence, virtually all of the data on tests conducted using the 13-mode cycle on a chassis dynamometer has been from Europe.

Transient test cycles are of two types: first the “geometric” cycles that have been used historically to test trucks and buses, and second, the “realistic” cycles that are now in use in the U.S. These cycles are discussed below in the context of a chassis dynamometer based test.

3.2 STEADY-STATE 13-MODE TEST

Substantial work towards the development of a chassis version of the 13-mode engine certification test has been conducted in Europe. In principle, the steady state test is relatively simple to perform, as the engine speed and load must be held steady at ten specified speed/load points, and three idle points. While engine speed can be easily measured off the tachometer, the determination of engine load other than rated maximum is difficult on a chassis dynamometer.

In the European project “Diesel-controle methode” (Van Gompel and Verbech:1993), a measuring method was developed to carry out a 13-mode test with heavy-duty diesel engines on a chassis dynamometer. A description of this optimised measuring method follows, and the activities for this measuring method must be carried out in the order described below.

Vehicle Instrumentation

The vehicle must be instrumented to measure:

- engine speed;
- exhaust gas back pressure;
- inlet depression;
- fuel, oil and constant temperature;
- exhaust gas temperature.

The test also requires use of certification quality diesel fuel if the results are to be compared to certification tests.

Adjustment of Rear Axle Weight

After completion of the instrumentation, the vehicle is placed on the chassis dynamometer, and the optimum axle weight is set. By means of a lifter or a pull-down device, the unloaded wheel pressure is lowered or raised, in order to achieve the optimum axle weight. This optimum axle weight ensures that the sum of rolling resistance losses and slippage losses is minimal, so that heat development in the tyres is limited during the 13-mode test.

Determination of Dynamic Wheel Radius

After the optimum axle weight has been established, the average dynamic wheel radius is determined. This is done by driving without any load in all gears at an engine speed corresponding to the intermediate speed. The speed of the rollers is used to determine the dynamic wheel radius for each separate gear. The average dynamic wheel radius is then compared with the static wheel radius. In this way, the specified ratios of the transmission and rear axle are checked whether they match the actual transmission ratios.

Power Measurement/Lambda Check

After the complete vehicle has been warmed up on the chassis dynamometer, a power measurement and Lambda check are carried out. At three RPM test-points of the 13-mode test (idle, MT-100 and MR-100) all the parameters are measured which are also measured in the 13-mode test. (The test RPM of these three test points can be obtained from the type-approval certificate). Using the measured values, the Lambda is calculated at each test point on the basis of air/fuel consumption and from the composition of the exhaust gas emission. If the Lambda values between the two full-load test points deviate by more than five percent, this points to a possible leak in the inlet or exhaust sections. After any fault has been rectified, a new check measurement is carried out. If the differences between the Lambda values are below five percent, the calculated engine power is compared with the type-approval documentation. For an engine power which is too low in MR-100 (difference less than five percent), the full-load curve is redefined in order to determine the test speeds for the 13-mode test. By means of the calculated engine power at MT-100 and MR-100, the test settings for the individual modes are determined.

During the course of the European in use compliance program (1994-1995) the number of test points for the values measured was increased. On the one hand, these steps were taken to make a more precise determination of any deviations or malfunctions in engine behaviour possible so as to facilitate discovery of the cause of the deviations. On the other hand, the Lambda check was used to permit comparison with the type-approval test. In this way conditions identical to the type-approval test has been achieved in practically all cases.

Chassis Dynamometer Setting

From the measured engine power at MT-100 and MR-100, the settings are determined for the 13-mode test. For each mode-point the optimum gear ratio is determined, at which heat development in the tyres is minimal. In order to avoid damage to the truck's own tyres, but more specifically since the rolling resistance of these tyres is unknown, separate wheels with test tyres are mounted. The test tyres should have known rolling resistance coefficients measured from tests. Subsequently, the optimum gear ratio is approached by selecting the correct gear. Using this transmission ratio the driving speed is calculated, as well as the corresponding brake force per mode-point. Due to the technical limitations of a specific chassis dynamometer, in some cases a different transmission ratio must be chosen. The driving speed and the corresponding brake force are then re-determined. For trucks provided with a low and a high gearing, all the chosen speeds must be in the same gear.

Emissions Measurement

Emissions measurements are carried out in accordance with the procedures for the engine based 13-mode test. This involves adjusting the exhaust back pressure and exhaust split into the dilution tunnel for PM sampling. The load for each mode is adjusted to match specifications within one minute, and each test point is held for at least five minutes. Particulate emissions are measured towards the end of the five minute period, with the sampling time proportional to the weighting of each mode. Final results for gaseous emission are calculated based on each modes results, weighted by the appropriate factors.

These methods have been found to yield results that correspond well with engine based 13-mode tests.

3.3 GEOMETRIC TEST CYCLES

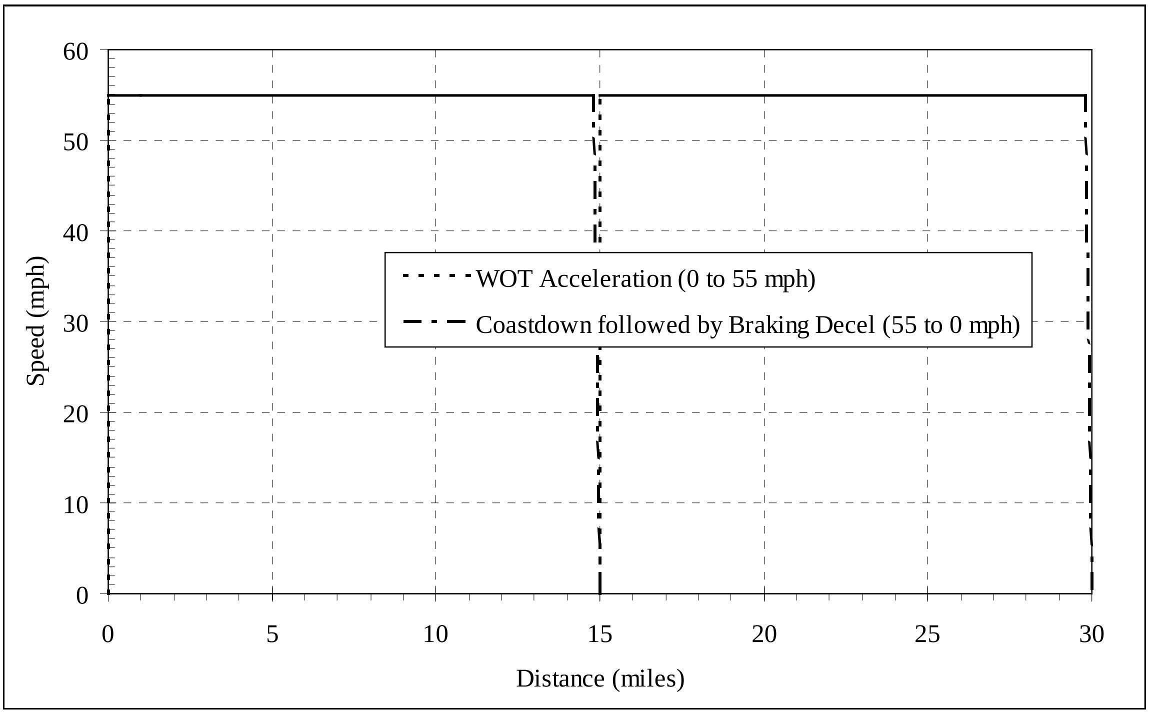
Geometric (or stylised) test cycles for heavy duty vehicle testing have been in existence for two decades or more. Generally these cycles are characterised by a one or more series of idle, acceleration, steady state cruise, and deceleration events that when presented in terms of speed versus cycle time or speed versus cycle distance produce cycle traces that are basically geometric (often sawtooth like) in shape. In effect, these cycles do include a treatment of transient (i.e., acceleration based) emissions events that are omitted from the steady state modal cycles discussed above, but such treatment is most often simplistic in nature and cannot really be viewed as reflective of anything but a very general representation of in-use operational characteristics.

The primary rationale for this simplistic treatment can be traced to the fact that these cycles were designed for either test track or on road application (heavy duty chassis dynamometer setups were not common when most of these cycles were developed and neither are they today). Nevertheless, a substantial number of geometric cycles have been developed for a wide range of heavy-duty vehicle applications and the majority of in use emissions research conducted over the last several years has been based on the use of one or more of these cycles.

Perhaps the best place to begin a review of geometric test cycles is, as was the case for modal cycles, with the handbook of SAE standards. SAE standard J1376 includes a series of cycles designed to determine heavy-duty truck and bus fuel economy. While emissions measurement was not a central focus of J1376 development, the J1376 cycles have probably been used more often in support of in use heavy-duty vehicle emissions testing than any other emissions test cycle. In fact, one component of SAE J1376, the Central Business District (CBD) portion of the Transit Coach Design Operating Cycle (TCDOC) is probably the most widely used in use heavy duty vehicle emissions test of the last 15 years (excluding simplified smoke measurement tests). The fact that these cycles were not explicitly designed for emissions evaluation is not significant. The issues of importance to emissions researchers were ones of cycle standardisation and a perception of reasonable, if not absolute, consistency between the test cycle and actual vehicle operating cycles. While this latter presumption is certainly not accurate given the generalised nature of the geometric cycles and even the former presumption is questionable for reasons which are discussed in more detail below, the perceived standardisation and lack of better alternative cycles has led to widespread use of (at least some of) the J1376 cycles.

Figure 3-1 presents the SAE J1376 Long Haul Test Cycle. As is obvious, this cycle is intended to reflect interstate highway operation and is composed of two repetitions of a sub cycle consisting of wide-open throttle (WOT) acceleration from zero to 55 miles per hour (mph), immediately followed by a steady state cruise at 55 mph through a distance of 14.79 miles and a coasting/braking deceleration applied to bring the vehicle back to a speed of zero mph at a distance of 15 miles. The cycle also includes a three-minute idle period after completion of the second 15-mile sub cycle.

Figure 3-1: SAE J1376 Long Haul Cycle



In some ways, such as the use of distance versus speed rather than time versus speed as the fundamental units of cycle definition, the long haul cycle anticipates the latest "route" based transient cycles discussed below. However, its relative simplicity combined with its extended 30-mile cycle length has precluded the development of any significant emissions database using the Long Haul Cycle.

To reflect inter- and intracity operational characteristics, SAE J1376 also includes two versions of a Short Haul Test Cycle. The "preferred" Short Haul Test Cycle is composed of two repetitions of a sub cycle consisting of a half throttle acceleration from zero to 10 mph, immediately followed by a series of WOT accelerations and steady state cruises (at 40, 48, 56, 64, 72, 80, and 88 kph) through a distance of 7.29 miles, a coasting deceleration to 24 kph, a braking deceleration to bring the vehicle back to a speed of zero mph at a distance of 12 km, and a 60 second idle period. Figure 3-2 presents one sub cycle of the preferred Short Haul Test Cycle (excluding the 60 second idle period).

Figure 3-3 presents a single sub cycle (excluding preceding and following idle operating periods) of an "alternative" Short Haul Test Cycle designed primarily to handle instances where a closed test track is not available and testing must occur on open roadways. The alternative cycle is twice as long, but eliminates several of the component acceleration and steady state modes of the preferred Short Haul Test Cycle.

Figure 3-2: SAE J1376 Short Haul Cycle

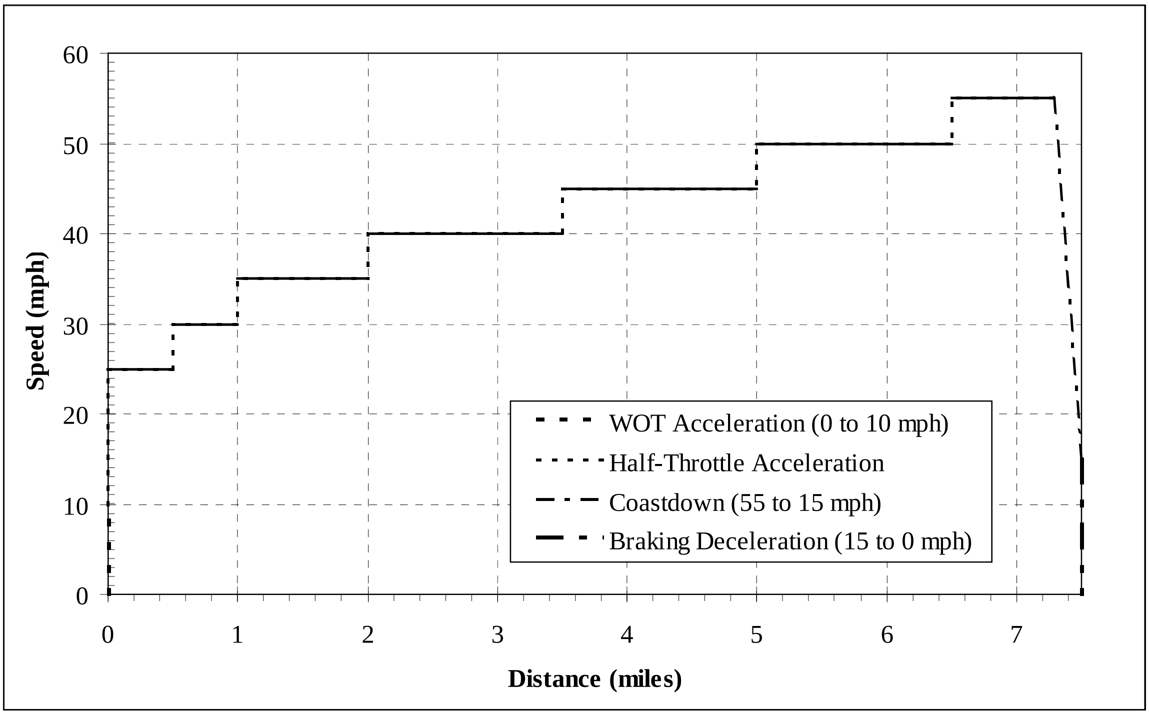
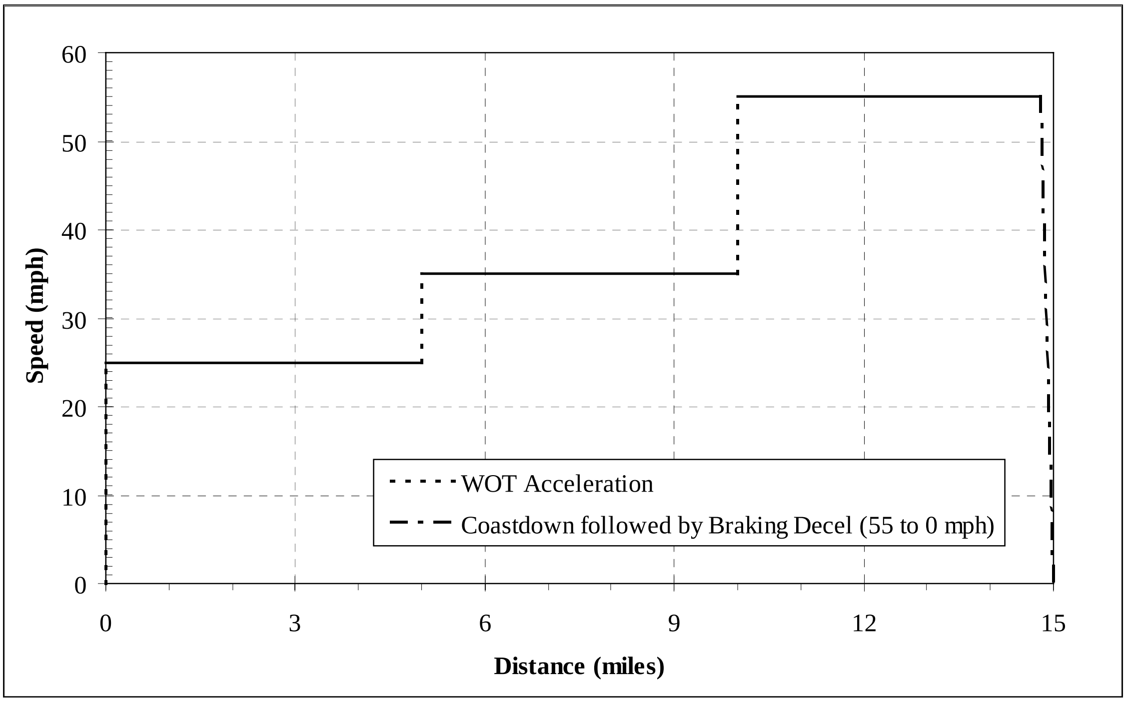


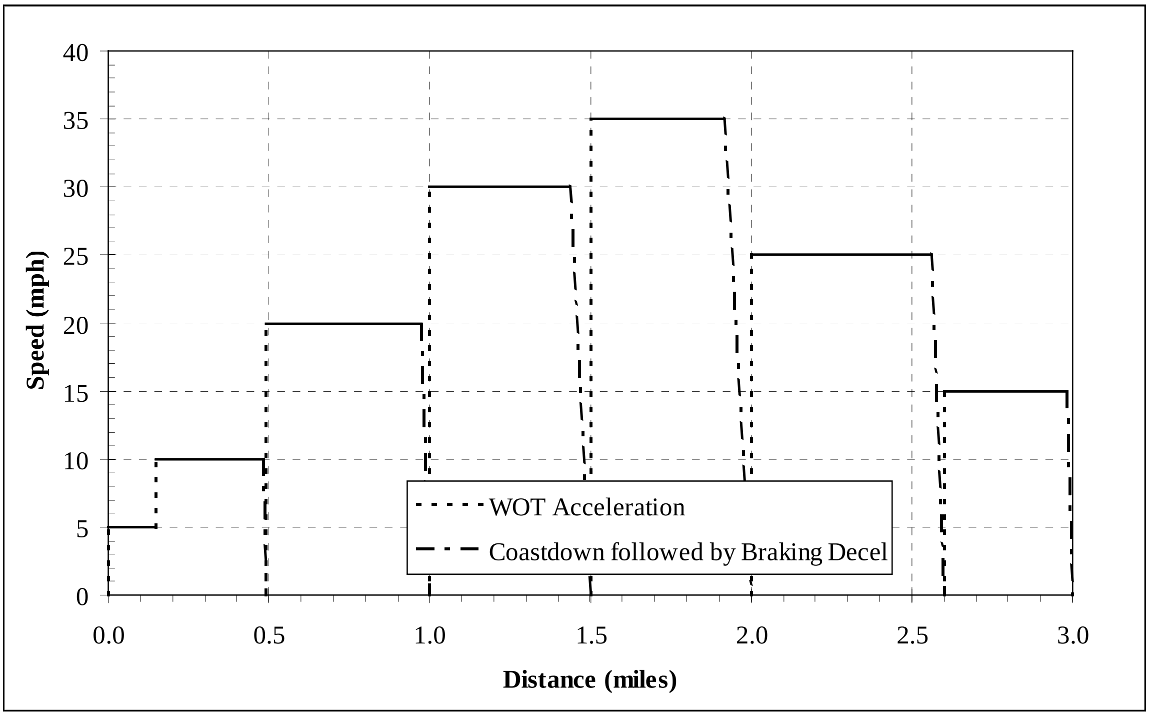
Figure 3-3: SAE J1376 Alternate Short Haul Cycle



Specifically, the alternative Short Haul Test Cycle is composed of two repetitions of a sub cycle consisting of a 60 second idle period followed immediately by WOT acceleration and steady state cruise modes (at 40, 56, and 88 kph) through a distance of 23.77 km, a coasting/braking deceleration to bring the vehicle back to a speed of zero mph at a distance of 24 km, and a second 60 second idle period. Like the Long Haul Test Cycle, neither the preferred or alternative Short Haul Test Cycles have been utilised to any significant extent in use emissions testing programs.

The SAE J1376 preferred and alternative Local Test Cycles are designed to reflect intracity pickup and delivery operational characteristics. Figures 3-4 and 3-5 present a single component sub-cycle of each.

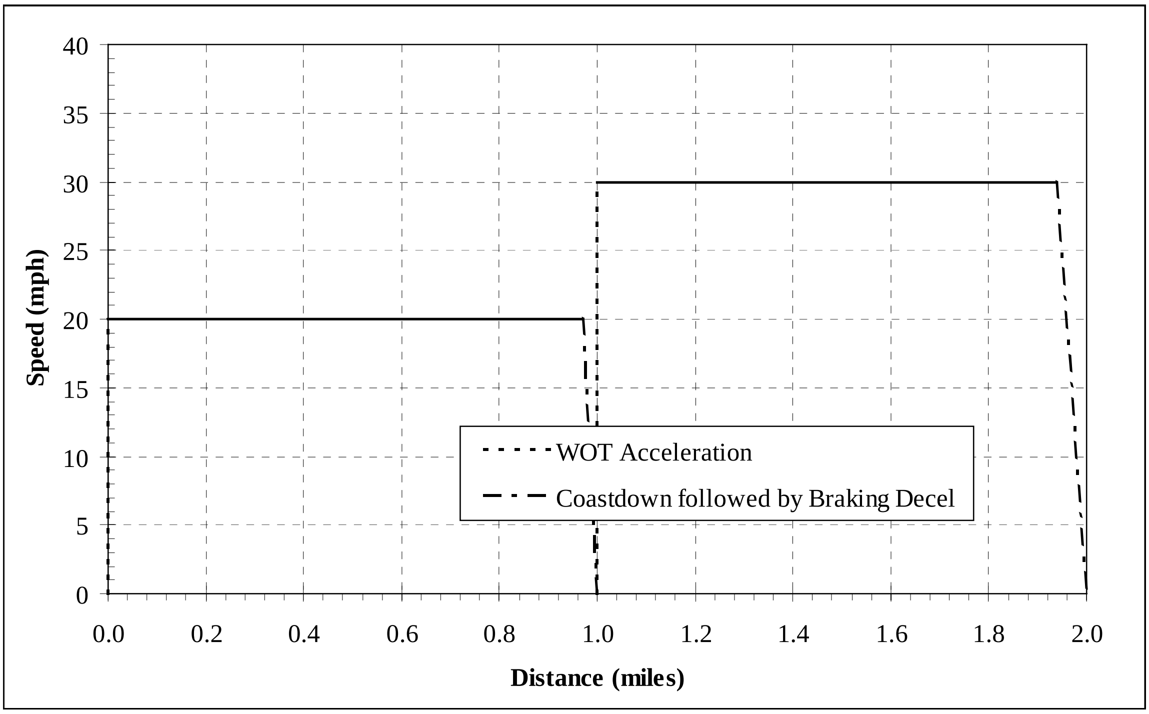
Figure 3-4: SAE J1376 Local Test Cycle



One sub cycle of the preferred Local Test Cycle consists of a 30 second idle period plus six distinct WOT acceleration / steady state cruise / deceleration / idle events. The first event differs in characteristic from the other five in that it includes two WOT accelerations (between zero and 8, and 8 and 16 kph) and steady state cruise (at 8 and 16 kph) components. The other five events are defined by steady state cruise speeds of 40, 48, 56, 40, and 24 kph). The six sub cycle events each end with a 20 second idle period following coasting / braking decelerations at 0.8, 1.6, 2.4, 3.2, 4.2, and 4.8 km respectively.

The overall cycle distance, considering two repetitions of the six-event sub cycle, is three miles and includes five minutes of idle time. The alternative Local Test Cycle eliminates four of the six sub-cycle events, but increases the number of sub-cycle repetitions to 12. The two retained sub-cycle events, which are preceded by a 20 second idle period, comprise WOT acceleration / steady state cruise / deceleration / idle periods defined by steady state cruise speeds of 32 and 48 kph, each period covering one mile and ending with a 20 second idle.

Figure 3-5: SAE J1376 Alternate Local Test Cycle



The overall alternative Local Test Cycle distance, considering 12 repetitions of the two event sub-cycle, is 24 miles and includes 12 minutes of idle time. Once again, neither of these cycles appears to have been utilised to any significant extent in in-use emissions testing programs. Researchers such as Perkins have developed modified versions of the Local Test Cycle to better represent specific heavy duty vehicle operational cycles, but even these cycle variations have functioned as little more than analytical exercises, having supported no significant in use testing programs.

The same cannot be said of the last test cycle defined in the SAE J1376 standard. The Transit Coach Design Operating Cycle (or at least a component thereof) has been used extensively in support of in use emissions test programs in the U.S. The cycle, presented in Figure 3-6, consists of stylised repetitions of three sub cycles and, as the name implies, is designed to reflect transit bus operational characteristics.

The CBD Sub Cycle is intended to reflect urban stop-and-go passenger service, the Arterial Sub-Cycle a less demanding moderate speed operation, and the Commuter Sub-Cycle high-speed suburban operation. The three sub cycles are presented in more detail in Figures 3-7 through 3-9 respectively.

Figure 3-6: SAE J1376 Transit Coach Design Operating Cycle

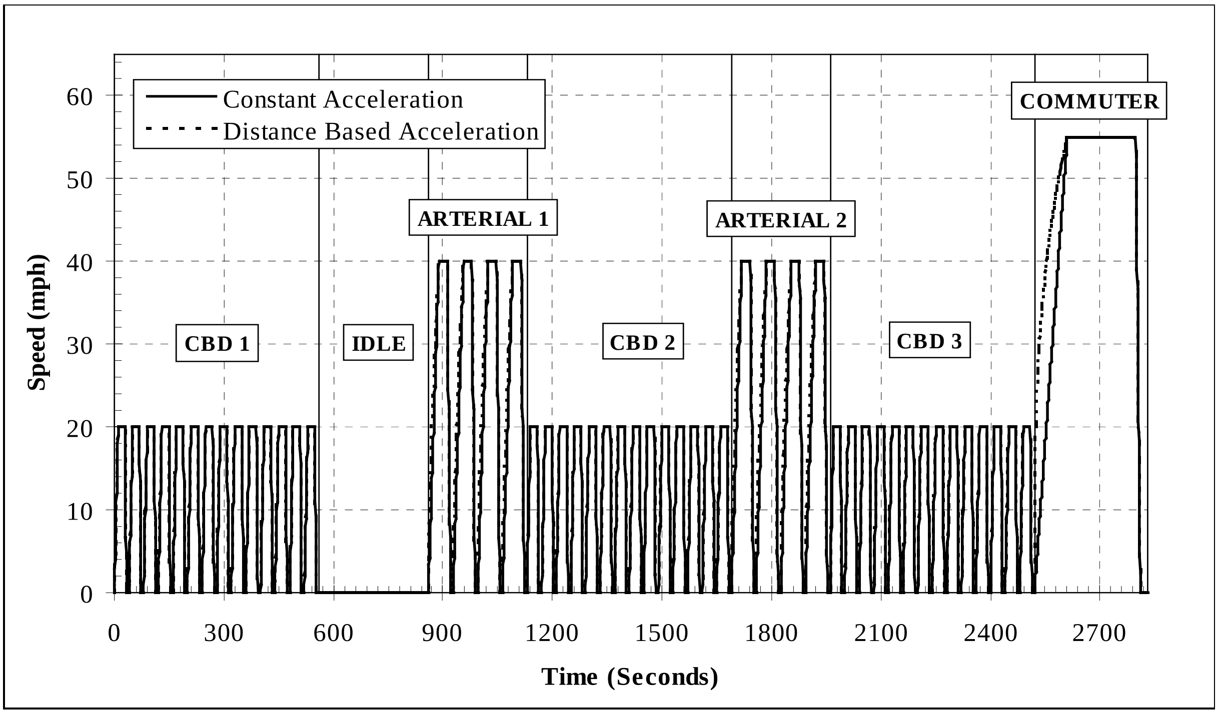


Figure 3-7: SAE J1376 Transit Coach CBD Sub-Cycle

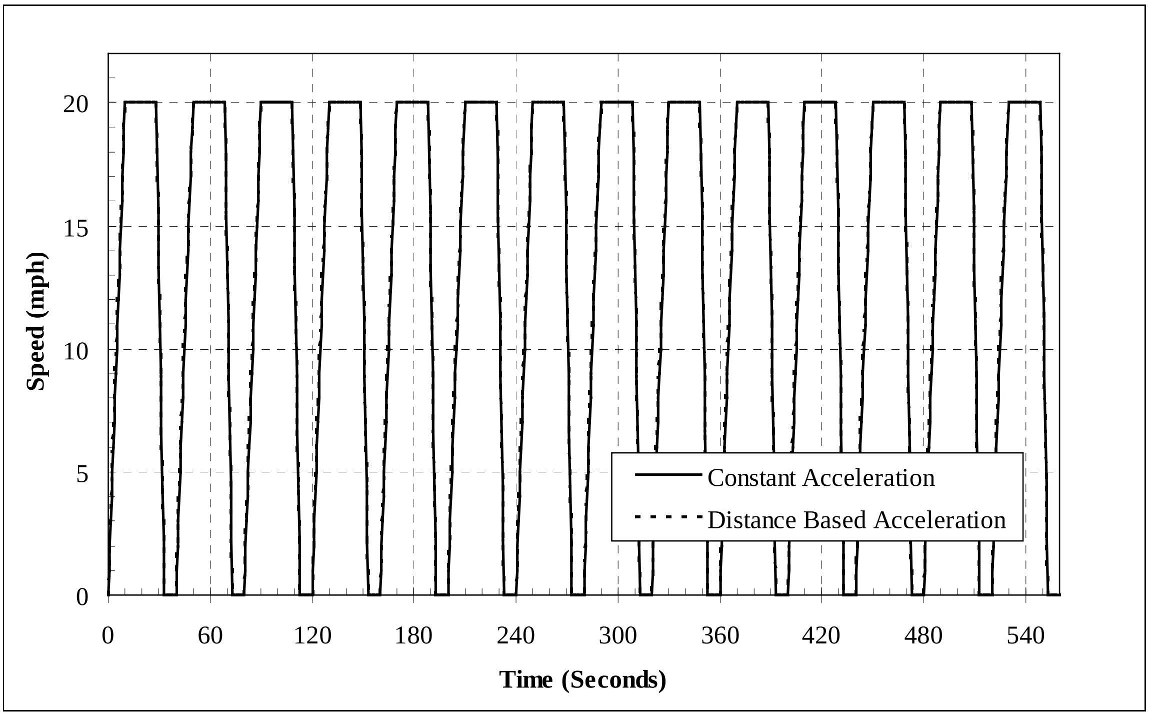


Figure 3-8: SAE J1376 Transit Coach Arterial Sub-Cycle

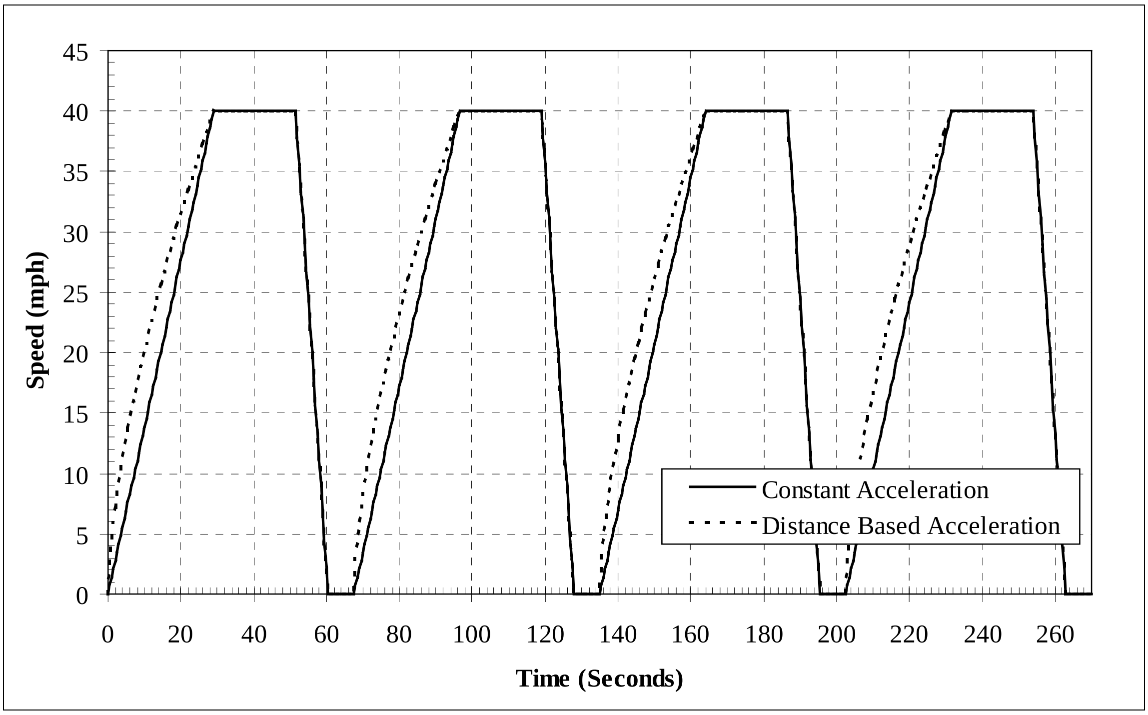
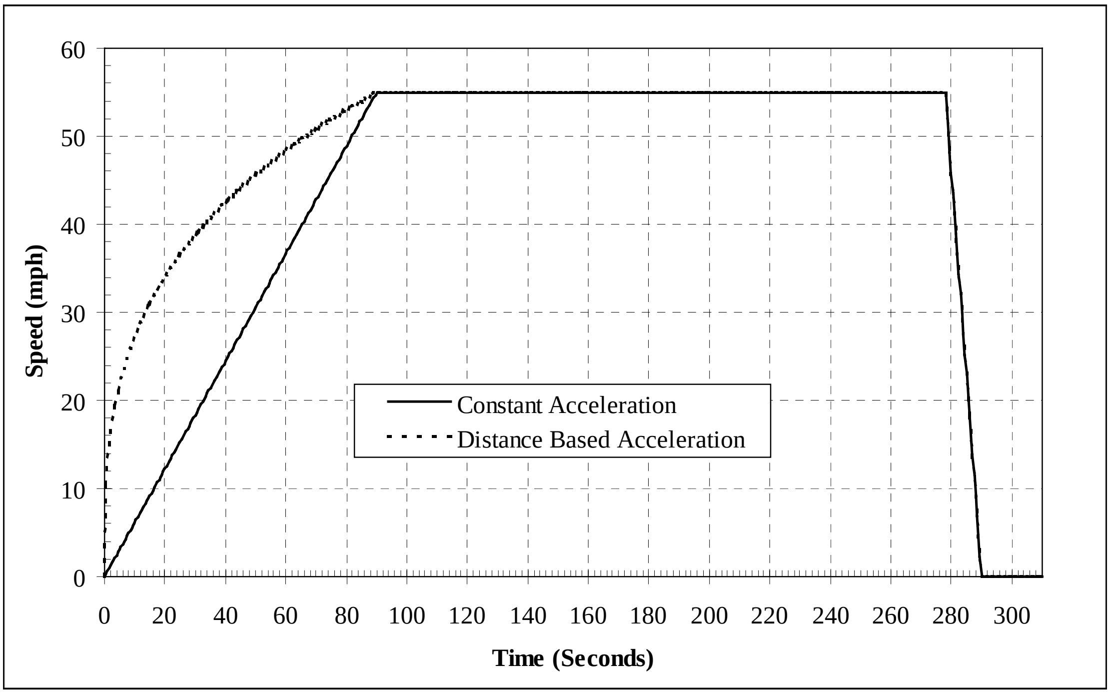


Figure 3-9: SAE J1376 Transit Coach Commuter Sub-Cycle



It is the CBD Sub Cycle that has been used to support extensive U.S. in use heavy-duty vehicle emissions testing, primarily but not exclusively targeting buses.

Unfortunately, the SAE J1376 definitions of the TCDOC are both sufficiently vague and sufficiently inconsistent to require significant interpretation to reproduce, thereby rendering significant variability to the CBD (as well as the Arterial and Commuter) cycles used by various research organisations. For example, the CBD steady state cruise speed is clearly defined in the

J1376 standards as 20 mph, but the defined cruise distance of 540 feet is not completely consistent with the defined cruise time of 18.5 seconds. Simple calculations demonstrate that a 540 foot cruise at 20 mph will take 18.41 seconds whereas an 18.5 second cruise at 20 mph will cover 542.67 feet. Similar (and often larger) inconsistencies plague the acceleration and deceleration portions of the sub cycle as well as corresponding portions of the Arterial and Commuter sub cycles. Unfortunately, these inconsistencies are often larger than simple round off errors would allow.

Nevertheless, to a large extent, these inconsistencies can be dismissed if the cycle times (as opposed to cycle distances) are taken as correct since, when totalled, the indicated component event times do sum to the indicated sub cycle times while similar agreement between indicated component distances does not exist.

Unfortunately, the simplicity of such an approach to actual TCDOC sub cycle construction breaks down for the acceleration portions of the sub cycles. The figures included in the SAE J1376 standard clearly depict the TCDOC acceleration events as non-linear [2], with acceleration rates declining over time, while a simple cycle construction treatment based on stated acceleration times yields constant acceleration rates. Various researchers have responded differently, some relying on constant accelerations, others constructing declining acceleration curves using typically undocumented techniques. For this reason, cycles initially portrayed as identical have been found to differ from research organisation to research organisation.

Unfortunately, the unintended side effect is that emissions portrayed as measured over the same cycle are subject to uncertain levels of variation due to cycle specific, rather than vehicle specific, influences. For example, West Virginia University (WVU), a primary researcher of in use heavy duty vehicle emissions, uses a straight-line acceleration “curve” in their interpretation of the CBD cycle, while Environment Canada, having also performed extensive heavy duty vehicle testing over the CBD cycle, uses a declining acceleration approach.

Using the information incorporated in the SAE J1376 standard, there is only one obvious means of constructing a viable declining acceleration curve for the acceleration portions of the CBD, Arterial, and Commuter Sub Cycles. If both the stated acceleration distance and the stated acceleration time are assumed to be correct (despite the obvious inconsistencies in these same parameters for the steady state cruise and deceleration portions of the cycles), and it is also assumed that the velocity curve produced during the declining acceleration period is continuous throughout the acceleration event, then there is only one acceleration solution which yields the “correct” distance travelled given the design acceleration period time (e.g., 10 seconds for the CBD Sub Cycle acceleration events) and post acceleration travel speed (e.g., 20 mph for the CBD).

The sub cycle speed versus time traces presented in Figures 3-7 through 3-9 incorporate both constant acceleration curves (as unbroken lines) and travel distance limited acceleration curves (as dashed lines) to illustrate the sensitivity of constructed cycles to researcher interpretation. Unfortunately, there is no way of knowing exactly what acceleration assumptions various researchers have utilised short of obtaining the actual speed versus time traces for the actual test cycles. This uncertainty combined with the general uncertainties created by the inconsistent

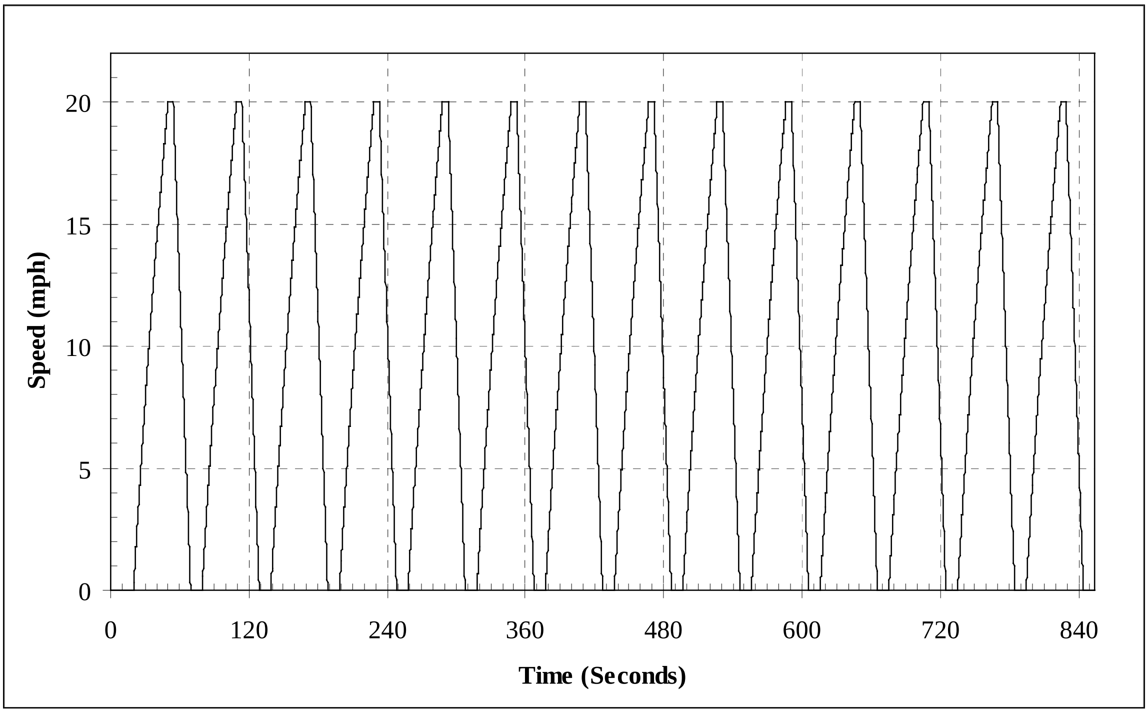
[2] Depicted cycle traces in the SAE J1376 standard are also not entirely reliable and clearly include undesirable artistic liberties. For example, the WOT and half-cycle acceleration events of the Long Haul, Short Haul, and Local Test Cycles are all depicted as “consuming” discrete, fixed travel distances when clearly individual vehicles will travel varying distances during such events depending on available engine power. Nevertheless, only the TCDOC depicts non-linear acceleration events. The figures presented in this paper attempt to minimize the impact of artistic license by depicting available power-controlled accelerations as instantaneous rather than as comprising a discrete travel distance (although clearly some variable distance will be traveled during the acceleration event).

time/distance values presented in SAE J1376 for the cruise and deceleration events creates the undesirable artefact of not being able to place a high degree of certainty in the comparability of test results obtained by different researchers, even when both portray the data as applying to the TCDOC or one of its sub cycles.

As alluded to above, West Virginia University has been a leading researcher in the area of in use heavy-duty vehicle emissions. To support various research projects, WVU has used test cycles developed by others as well as several cycles of their own creation, most of which can be categorised as stylised (or geometric) in nature. The majority of WVU's bus related emission work is based on the SAE J1376 CBD cycle as already described. However, WVU has found this cycle to be problematic for truck testing due to accelerations that are too aggressive for many candidate trucks. As a result, they have created a modified version of the CBD for truck testing.

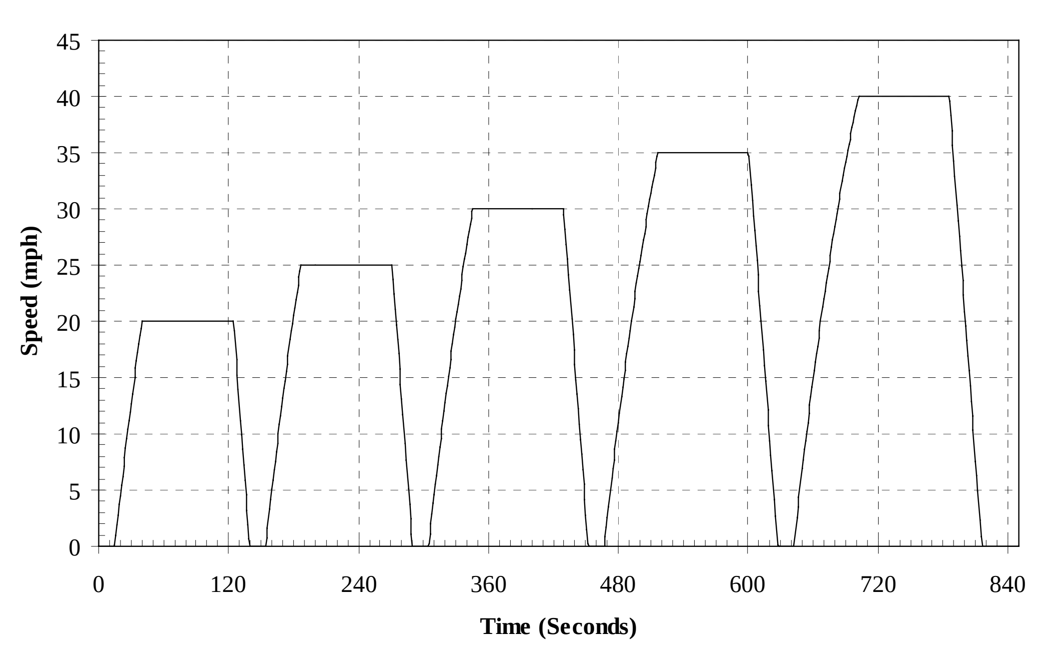
Figure 3-10 depicts the WVU Truck CBD Cycle, which essentially retains the same absolute speed ranges as the TCDOC CBD Sub Cycle, but with temporally expanded acceleration events and temporally restricted steady state cruise modes.

Figure 3-10: West Virginia University Truck CBD Cycle



Another geometric cycle that has been used extensively by WVU for heavy duty truck testing is the WVU Five Peak Cycle depicted in Figure 3-11 (Hoppie:1997).

Figure 3-11: West Virginia University Five Peak Cycle



Like the SAE J1376 TCDOC and the WVU Truck CBD, the Five Peak Cycle is defined on a speed versus time basis. However, WVU has correctly recognised that heavy-duty vehicles respond to the acceleration events of such cycles in often dramatically different fashions, and in ways not reflective of real world operation. While underpowered vehicles may operate at or near WOT during such events (even then potentially failing to "keep up" with the speed versus time trace), overpowered vehicles may be under exercised relative to the aggressive acceleration characteristics such vehicles commonly employ during real world operation. Real world accelerations are constrained only by vehicle performance and traffic conditions, with vehicles of any power-to-weight ratio possessing the capacity for WOT accelerations in unconstrained traffic conditions. Under a driving cycle which includes such WOT conditions, distance based (rather than time based) cycle definitions more accurately define behaviour across vehicles since highly powered vehicles have shorter time based acceleration periods than their lower power counterparts, but both ultimately travel the same distance between any two given points.

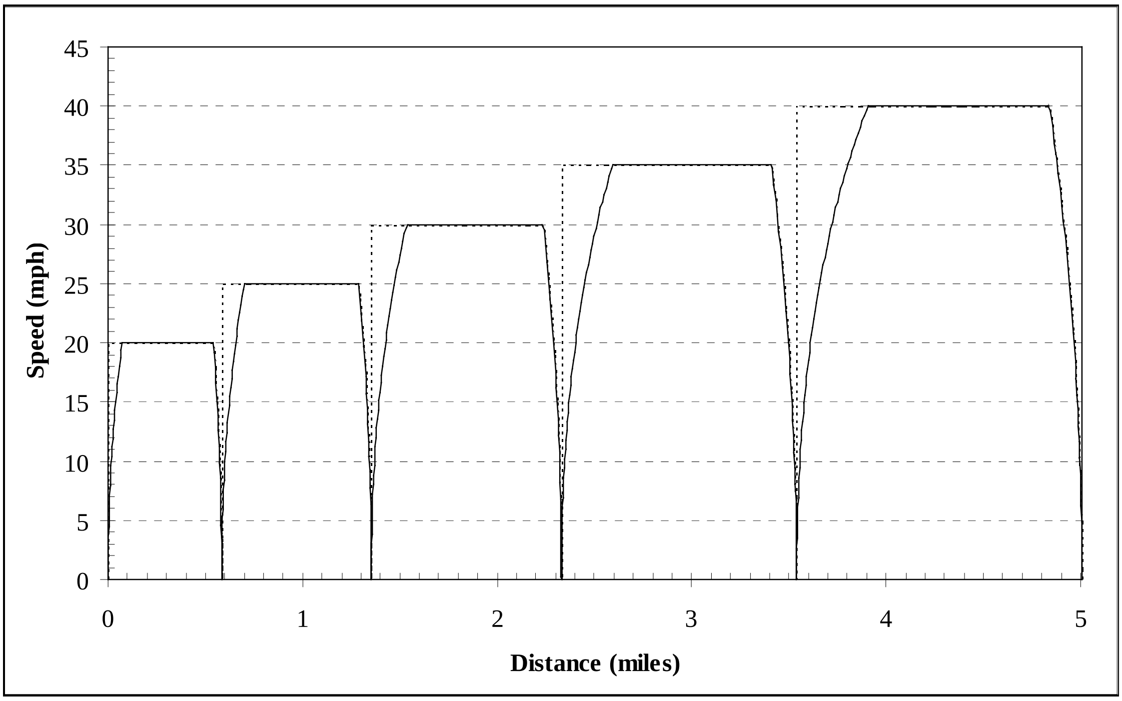
Moreover, WVU has conducted research that indicates that the measured emission rates of heavy-duty vehicles are quite dependent on test cycle acceleration characteristics. In a cooperative test program with the Colorado School of Mines (CSM), WVU has shown substantially different emission rates for the same vehicle driven over the same CBD test cycle, tracing the observed differentials to vehicle driver behaviour. WVU instrumentation does not include any tolerance bands on their speed/time drivers aid trace, while CSM instrumentation clearly depicts such bands and drivers were observed to "modulate" their throttle behaviour during acceleration periods to "take advantage" of the allowable tolerances. The net effect were measured emission rates that differed by as much as 10 percent to 20 percent for NO_x and 80 percent for carbon monoxide (CO).

In an effort to create a more realistic treatment of the acceleration behaviour of heavy duty vehicles, WVU created a modified version of their Five Peak Cycle (Clark:1998). Designated as the WVU Five Mile Route, the test cycle replaces the timed accelerations of the Five Peak Cycle with WOT accelerations and distance based cycle definitions, recalling the approach utilised for all SAE J1376 cycles except the TCDOC. Figure 3-12 presents the basic WVU Five Mile Route Cycle.

The cycle clearly continues to be geometric in design. The solid speed versus distance trace of Figure 3-12 is nothing more than a re-expression of the Figure 3-11 speed versus time trace for the WVU Five Peak Cycle. However, the dashed line speed versus distance trace is what vehicle drivers actually follow during the test cycle. During acceleration events, the vehicle always lags the instantaneous speed change employed in the cycle trace, "forcing" the driver into a WOT acceleration mode until such time as the steady state cruise speed is attained. Total cycle time will vary in accordance with available engine power, but all test vehicles will travel the same five-mile distance regardless of overall cycle time.

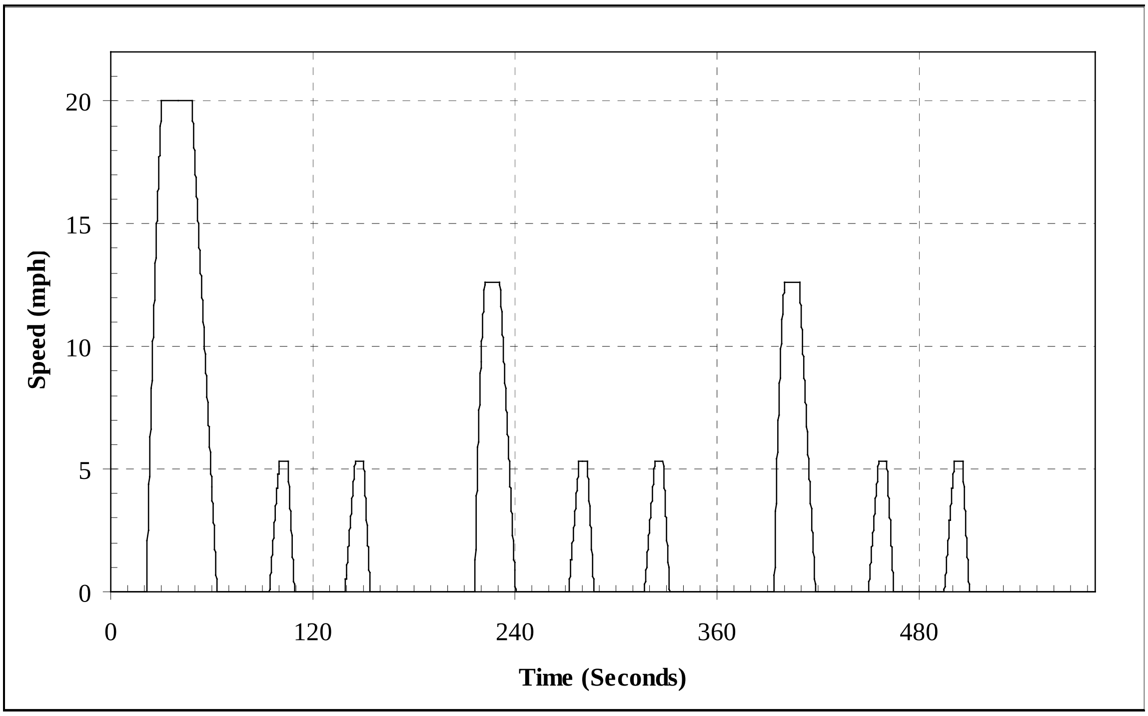
Intuitively, the distance based cycle (or route) is more reflective of actual vehicle behaviour since all vehicles are allowed to "arrive at their destination" in accordance with their respective power characteristics. WVU demonstrated that a 350 horsepower truck run over both the time based Five Peak Cycle and the corresponding distance based Five Mile Route Cycle emitted about 6 percent more NO_x and 40 percent more CO over the distance based cycle. Although this comparison clearly demonstrates the sensitivity of heavy-duty vehicle emissions to the acceleration characteristics of the test cycle, absolute emission differences will vary across trucks in accordance with truck power-to-weight ratios.

Figure 3-12: West Virginia University Five Mile Route Cycle



The WVU Five Mile Route Cycle is representative of the most recent examples of geometrically constructed heavy-duty vehicle driving cycles. Several of the cycles described above have been used to support in use heavy duty vehicle emissions testing, most notably the CBD, Arterial, and Commuter Sub Cycles of the TCDOC (primarily, but not exclusively, for testing programs targeting buses), the WVU Truck CBD Cycle, the WVU Five Peak Cycle, and the WVU Five Mile Route Cycle. The only additional geometric cycle that appears with any significant frequency in heavy duty testing programs is the New York City Garbage Truck Cycle (NYGTC). As depicted in Figure 3-13, the NYGTC is a very low speed cycle that includes nine short acceleration / cruise / deceleration events interrupted by substantial periods of idle.

Figure 3-13: New York City Garbage Truck Cycle



3.4 REALISTIC TEST CYCLES

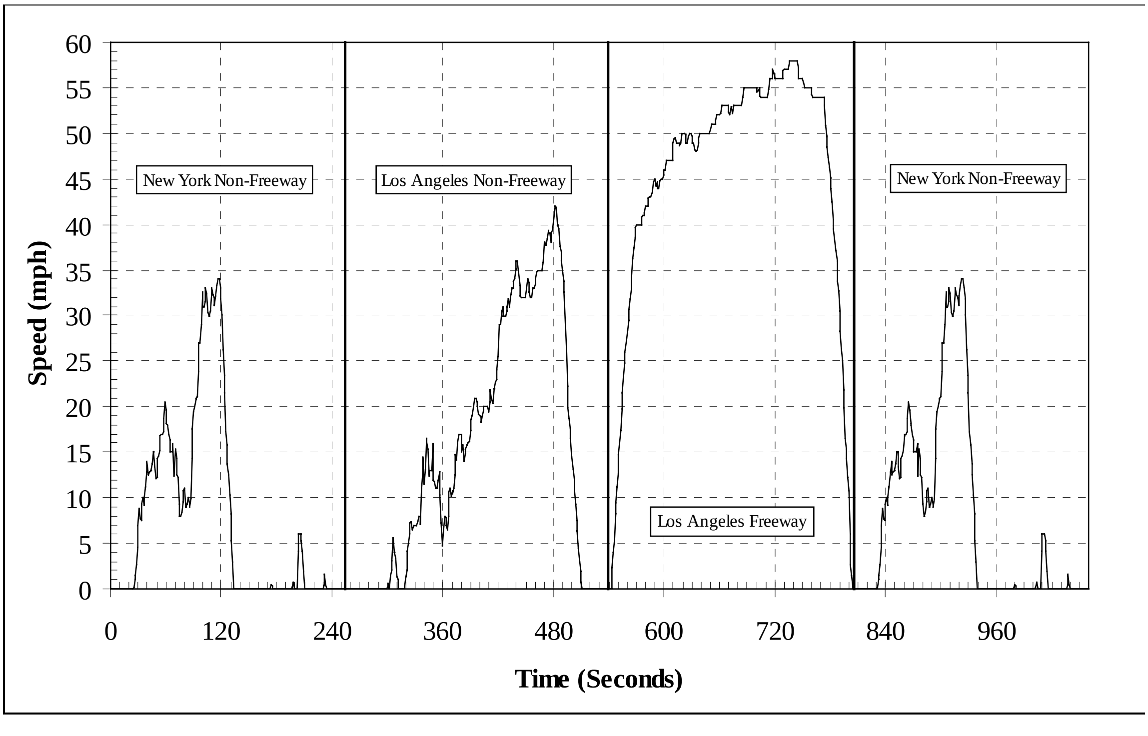
Transient (or realistic) test cycles differ from geometric cycles primarily in that they are designed to simulate continuously varying operational characteristics, presumably reflective of specific real world behaviour. Like geometric cycles, transient driving cycles for heavy duty vehicle testing have been in existence for at least two decades. The development of additional cycles continues to this day as researchers strive to develop cycles that are both representative of a wide range of real world behaviour for a wide range of vehicles and, ideally, comparable to engine based emissions certification data. Significant advancements in transient cycle development over the last several years have resulted in the establishment of analytical methods that hold the promise of eventually promoting the adoption of a “standard” method of heavy-duty vehicle emissions testing. Unfortunately, such standardisation is not yet in place and individual research programs continue to utilise independent and usually incomparable test cycles.

The earliest (and most often utilised) set of realistic heavy duty vehicle test cycles were derived from heavy duty vehicle operational data collected under a research program sponsored jointly by the U.S. Environmental Protection Agency (EPA) and the Coordinating Research Council (CRC) in the mid-1970’s. This data collection program, known as the CAPE-21 program, included the collection of operational data for 44 trucks and 3 buses in Los Angeles and 44 trucks and 4 buses in New York City. Synopses of the CAPE-21 program can be found in a number of references, but the program essentially consisted of the instrumentation and analysis of operational data collected from each of the program vehicles (France et al:1978). Perhaps somewhat surprisingly, given that it is 1970’s research, the CAPE-21 database and associated analyses produced virtually all of the heavy duty engine and vehicle transient driving cycles in general usage until very recently. This includes both the gasoline and diesel engine emissions certification cycles now in use in the U.S.

The CAPE-21 chassis cycle most often used to support in use heavy duty vehicle testing is the Federal Chassis Cycle for Heavy Duty Vehicles. This cycle is often referred to as the Schedule D cycle due to its incorporation into the U.S. Code of Federal Regulations (CFR) as 40 CFR Part 86, Appendix I, Section (d). The Federal Chassis Cycle is also the most misunderstood transient heavy duty vehicle cycle since it is often presumed to be the chassis equivalent of the Federal engine certification cycle. Unfortunately, this is not the case. While both the Federal engine and chassis cycles were developed from the same database, both were also formulated using independent Monte Carlo simulations of collected operational data [3]. Therefore, while they can be viewed as related, they are not equivalent. This is quite clear when one recalls that the engine cycles are not unique cycles, but are instead normalised to the specific torque and speed characteristics of the candidate test engine, whereas the chassis cycle is invariant regardless of engine performance characteristics.

Figure 3-14 presents the Federal Chassis Cycle (France:1978). As indicated, the cycle is actually composed of three sub cycles: one intended to be reflective of non-freeway operation in New York, one intended to be reflective of non-freeway operation in Los Angeles, and one intended to be reflective of Los Angeles freeway operation. These three cycles run consecutively, followed by a second execution of the New York sub cycle, comprise the full 1060 second Federal Chassis Cycle. The cycle is codified in the CFR as an evaporative emissions test cycle only, it has no official function for exhaust emissions testing. Researchers have found the aggressive accelerations of the Federal Chassis Cycle to be difficult to follow in both trucks with low power-to-weight ratios and trucks with unsynchronised transmissions. Nevertheless, the cycle has been used in several instances to support in use emissions testing programs, but future use appears to be limited given the "unrealistic" aspects of cycle operational characteristics.

Figure 3-14: Federal Chassis Cycle for Heavy-Duty Vehicles



[3] Although the references already cited include detailed explanations of the CAPE-21 cycle development process and should be consulted as appropriate, the basic cycle development process can be viewed as follows. Collected operational data were divided into thousands of candidate cycle segments through random selection. The candidate cycle segments were statistically compared to the overall CAPE-21 database and final composite cycles were selected on the basis of statistical comparison results, engineering judgment, and a balance of freeway and non-freeway and New York and Los Angeles cycle times. As a result, the final cycles do not consist of the actual operational characteristics of any one vehicle and may, in fact, reflect operational sequencing that has never been experienced in Los Angeles, New York, or elsewhere. Chassis cycle transients are an often cited problem area, where many cycle acceleration rates are very difficult to follow, especially in trucks with unsynchronized transmissions.

In addition to the Federal Chassis Cycle, the CAPE-21 database was used to develop several other "specialised" driving cycles. Figures 3-15 through 3-17 depict three of these cycles, the New York City Bus Cycle, the New York City Truck Cycle, and the New York City Composite Cycle, all of which have been used to various minor extents in heavy duty in use emissions testing programs.

All three cycles are dominated by very low speed operation. Because of the New York City focus of the testing, they are worthy of consideration as appropriate driving cycles for the in-use testing being performed in support of this Report. However, applicability elsewhere is limited given the high degree of congestion implied.

In recognition of the limitations associated with the CAPE-21 transient cycles and alternative geometric cycles, significant research into alternative transient cycles has taken place in the U.S. over the last several years. This research has been focused along two, mutually inconsistent, paths. One research path has focused on developing a heavy-duty chassis cycle that is comparable to the heavy-duty engine emissions certification cycle. This approach, by definition, requires the construction of a chassis cycle that is specific to each test vehicle, since the engine certification cycle varies in accordance with test engine performance parameters. The second chassis cycle development approach is focused on the creation of a cycle or cycles which reflect real world vehicle operation and which can accurately be applied to a wide range of heavy-duty vehicles.

Figure 3-15: New York City Bus Cycle

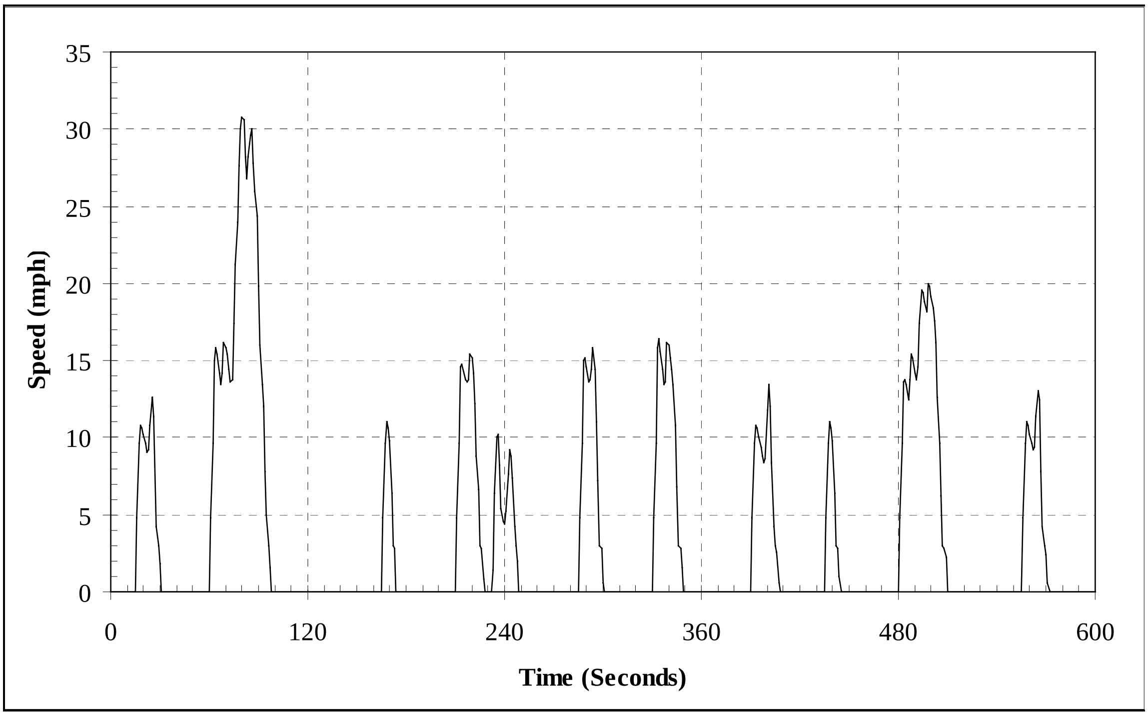


Figure 3-16: New York City Truck Cycle

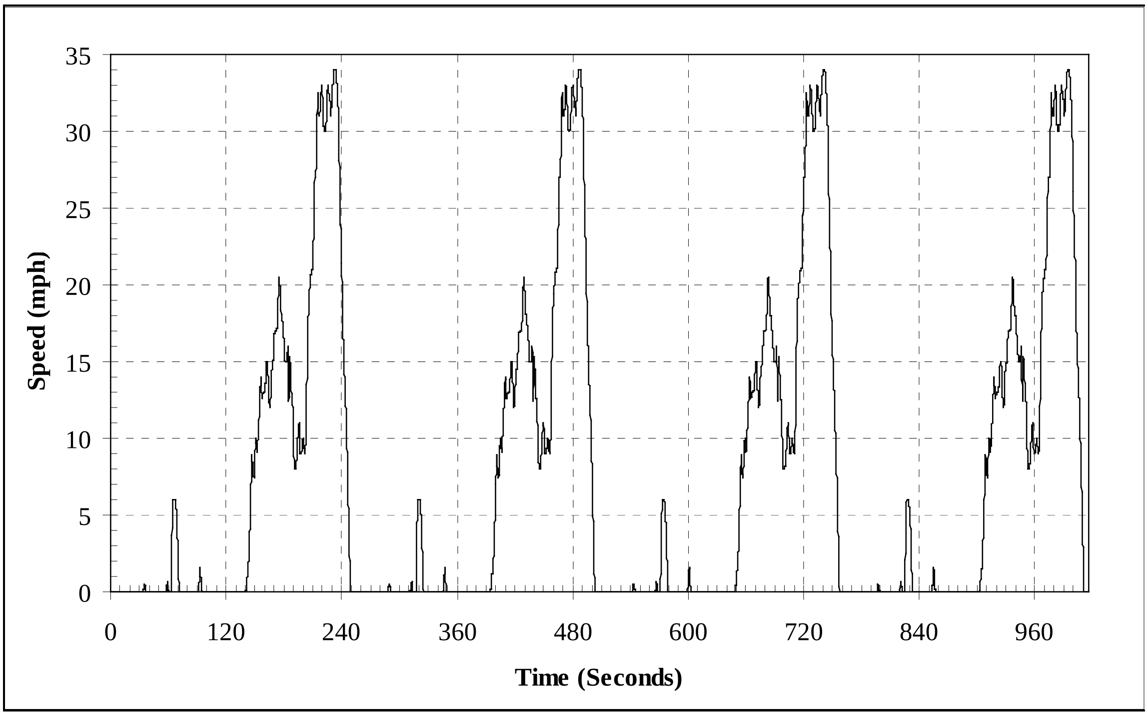
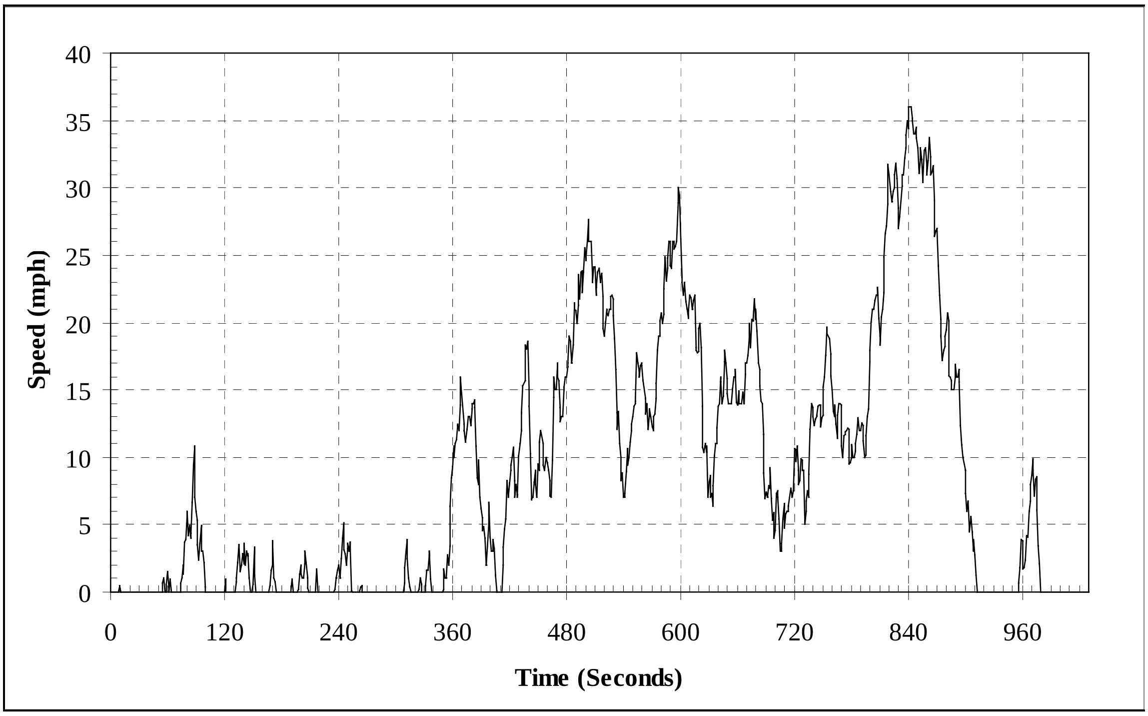


Figure 3-17: New York City Composite Cycle



Independent of these cycle development efforts is additional ongoing research aimed at constructing full range modal emission models which can be combined with any desired driving cycle to estimate in use emissions performance on the basis of comparatively simple modal emissions analysis. While preliminary work on full range modal models has been undertaken (Harris et al:1998), necessary demonstrations of agreement with direct chassis cycle measurements or correlation with engine cycle data have yet to be accomplished. Hence, these U.S. research efforts are not discussed in detail in this report. However, European (mostly German) efforts have focused on the development of modal emission models.

Significant progress has been made in developing a procedure for heavy-duty vehicle chassis based testing that is comparable to the engine based certification test. The current approach is based on developing a chassis cycle that approximates the energy demands of the engine certification cycle. This "conservation of energy" approach was originally suggested by researchers at WVU, with recent enhancements suggested by researchers with the U.S. EPA (Harris et al:1995).

Since energy demands are conserved across the engine and chassis cycles, the Heavy-Duty Vehicle FTP Energy Conservation Cycle [4] is vehicle specific, just like the engine cycle upon which it is based. The cycle construction process for a specific vehicle / test weight combination is quite intensive, but easily adaptable to software automation.

While the specific calculations necessary to create a chassis cycle with equivalent certification cycle energy demands are somewhat complex, the basic process can be summarised as follows:

1) Engine cycle torque and speed values are translated to horsepower,

2) Instances of positive torque at idle are eliminated as unrealistic (causing a decrease in total cycle energy of about 0.5 percent),

3) Thermal horsepower losses (drivetrain losses, aerodynamic drag, rolling resistance) are calculated and subtracted from engine horsepower to determine net motive power,

4) Vehicle speed is calculated as a function of mass and net motive power,

5) Based on certification cycle speed profiles, deceleration periods are assigned as either coasting or braking decelerations, and

6) Shift delays are added for manual transmission vehicles (these delays prolong the chassis cycle, but do not alter cycle energy).

7) Throughout cycle construction, gearing ratios are used to check available torque against torque required to meet vehicle speed demands. In instances where insufficient torque is available, cycle speeds based on maximum torque are substituted for successively calculated speeds until cycle energy demands equilibrate.

Figure 3-18 presents an example Heavy-Duty Vehicle FTP Energy Conservation Cycle driving trace.

This cycle was developed for a 1990 Freightliner tractor with a 325 horsepower Caterpillar 3176 engine towing a 45-foot cargo trailer. The gross combined weight was 45,800 pounds and the assumed inertial weight was 48,500 pounds. Road load forces were calculated as 277.12 + 0.1287 (velocity). It is important to recognise that, while not presented in Figure 3-18, a schedule of shift

---

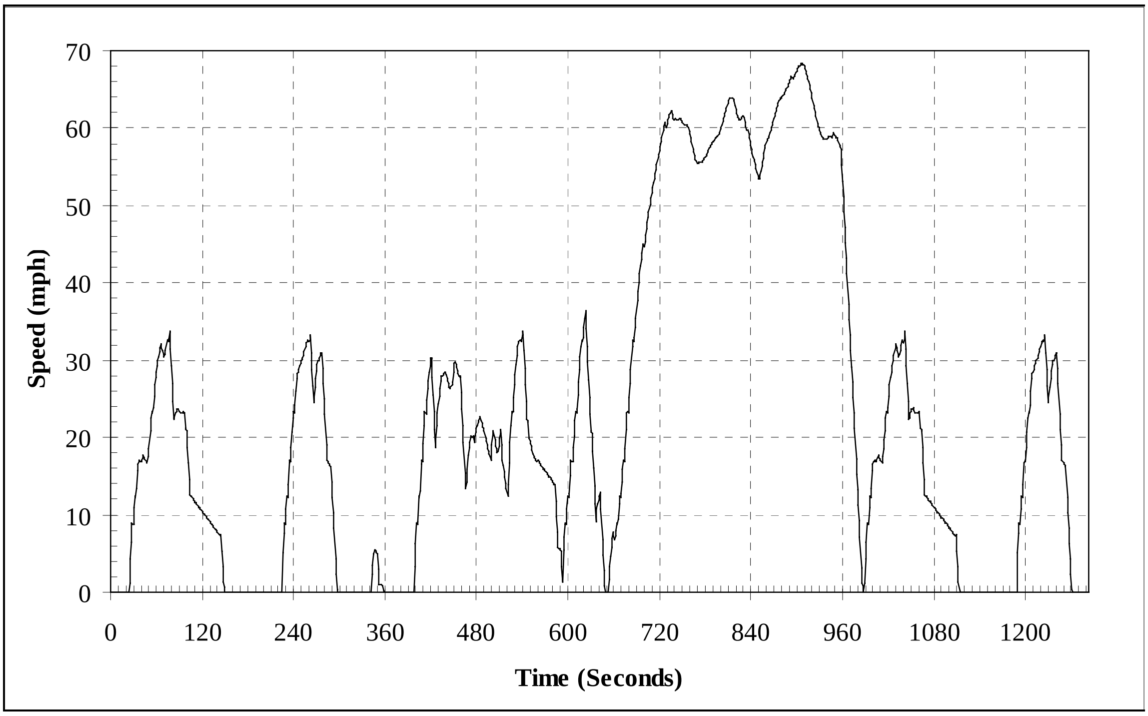
[4] This cycle naming convention is not extracted from the literature, but instead designed specifically for this Report. Reference terminology, such as "Second Generation Modified Energy Conservation Cycle (MEC / FTP2) (SAE:1982)" are not sufficiently descriptive for a general report such as this.

points, braking points, and clutch status events is required to ensure proper execution of the Energy Conservation Cycle.

Unlike the energy conservation approach which is intended to provide a mechanism for comparison of chassis test results to corresponding engine based certification test results, WVU has also been active in the recent development of "certification independent" route based driving cycles that can be used to test a wide range of heavy duty vehicles under conditions "typical" of real world operation.

This work can be viewed as an extension of WVU's work on the Five Mile Route Cycle that was described in Section 2.2.2 above. While the Five Mile Route Cycle was geometric in design, WVU's most recent route based driving cycle was developed to describe real world operational data collected in Akron, Ohio and Richmond, Virginia (Clark et al:1998).

Figure 3-18: Heavy-Duty Vehicle FTP Energy Conservation Cycle



WVU's approach to transient cycle development differs from that of the CAPE-21 program used to develop the Federal Chassis Cycle in two important respects.

First, data analysis is performed at the "micro trip" level of detail rather than on the basis of random operational event processing.

As defined by WVU, a micro trip consists of an actual vehicle trip between delivery stops. While micro trips were classified and processed as "highway," "suburban," "city," or "yard," all micro trips constitute an actual trip driven by one of the test vehicles instrumented by WVU. As a result, each component of the resulting driving cycle can be (and was) driven by at least one vehicle, whereas under the CAPE-21 Monte Carlo approach, no such certainty is assured. Complete cycle development (in a fashion that is similar to the CAPE-21 program) is based on the random selection of micro trips to create possible driving cycles. The subsequent selection of the "best" cycle is on the basis of the statistical similarity of selected performance criteria (velocity, velocity standard deviation, and cruise time) between the candidate driving cycle and the entire instrumented vehicle database.

Figure 3-19(a) presents a speed versus time trace for the WVU transient City/Suburban Heavy Vehicle Route Cycle (CSHVR).

The cycle is comprised of four micro trips from the Akron/Richmond database. However, as a speed versus time cycle, the CSHVR cycle presented in Figure 3-19(a) suffers from the same weakness which plagues many of the geometric cycles discussed in Section 3.3 and the Federal Chassis Cycle discussed above. Namely, the cycle is based on specific acceleration characteristics that may be too aggressive for some vehicles and not aggressive enough for others.

In actual real world situations, vehicles with more available power than the vehicle that drove the applicable micro trip will accelerate faster in free flow conditions and encounter speed restrictions (e.g., posted limits, traffic constraints) quicker than the micro trip vehicle. For underpowered vehicles, exactly the opposite will be true. As a result, WVU researchers undertook the additional step of converting the CSHVR to a speed versus distance format that better describes real world driving behaviour.

Figure 3-19(b) presents the CSHVR Cycle in its final speed versus distance format. The solid trace is simply a re-expression of the solid speed versus time trace of Figure 3-19(a). However, during actual WOT accelerations, the vehicle driver would actually be instructed to accelerate in accordance with the instantaneous acceleration characteristics indicated by the dashed portions of the trace.

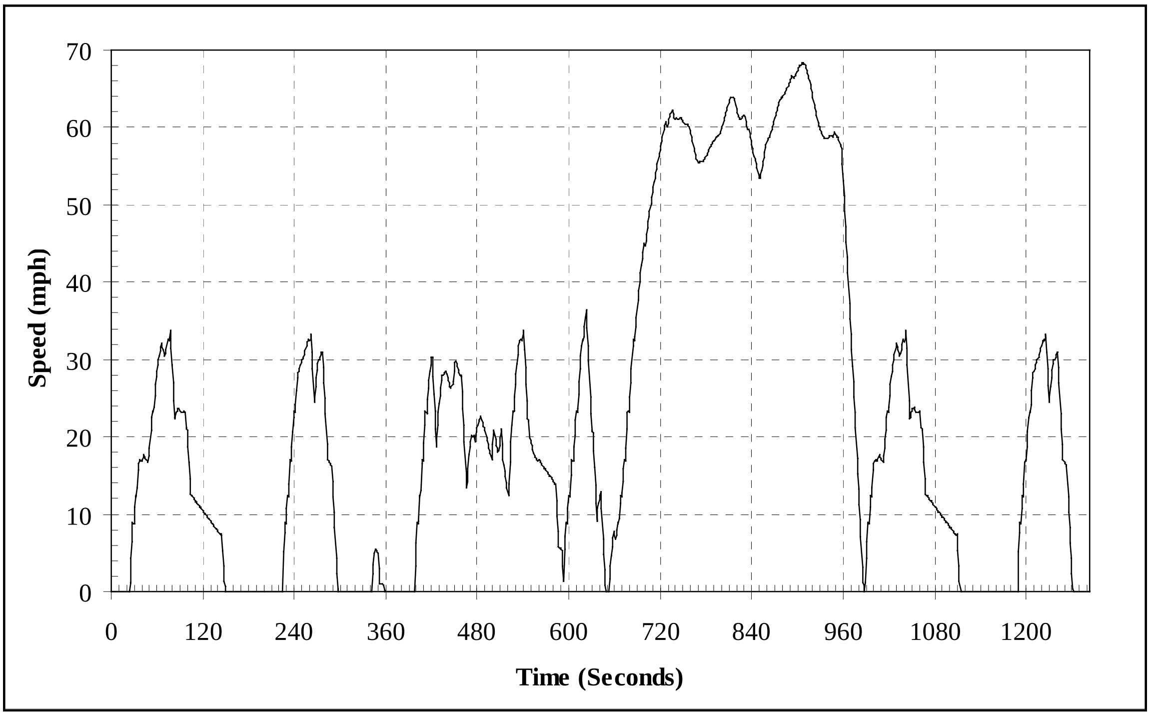
While these instantaneous accelerations certainly cannot be attained in practice, the vehicle driver will maintain WOT until the post-free acceleration speed in attained, and will subsequently “rejoin” the ideal cycle at the point where the ideal cycle distance equals the actual travelled distance. In this manner all vehicles drive the same distance, mimicking the behaviour that vehicles of differing power-to-weight ratios would exhibit had they actually driven the hypothetical route between the two terminus points. For illustrative purposes, the WOT acceleration points are also marked in Figure 3-19(a) as dashed traces, but it should be recognised that these traces are nonsensical in the context of speed versus time as the substitution of vehicle specific acceleration performance would either constrict or extend the time axis.

3.5 SUMMARY OF HEAVY DUTY TESTING OPTIONS

As discussed in the previous sections, myriad heavy-duty vehicle driving cycles have been developed over the last 25 or so years. Table 3-1(a) to (c) presents summary descriptive statistics for the various cycles discussed. The 13-mode cycle in its chassis variant is of interest in testing vehicles from the perspective of conformity with engine-based regulations. Since both Europe and the U.S. are likely to have a 13-mode certification test in the future (the ESC), development of 13-mode test capability is likely to be useful for some time to come. The major advantage of the 13-mode test is that no inertia weight simulation is required. Cycle statistics do not have any specific meaning in the context of the 13-mode, as it is used to provide a map of engine emissions under varied operating conditions.

Figure 3-19: West Virginia University City/Suburban Heavy Vehicle Cycles

(a) Speed Cycle



(b) Route Cycle

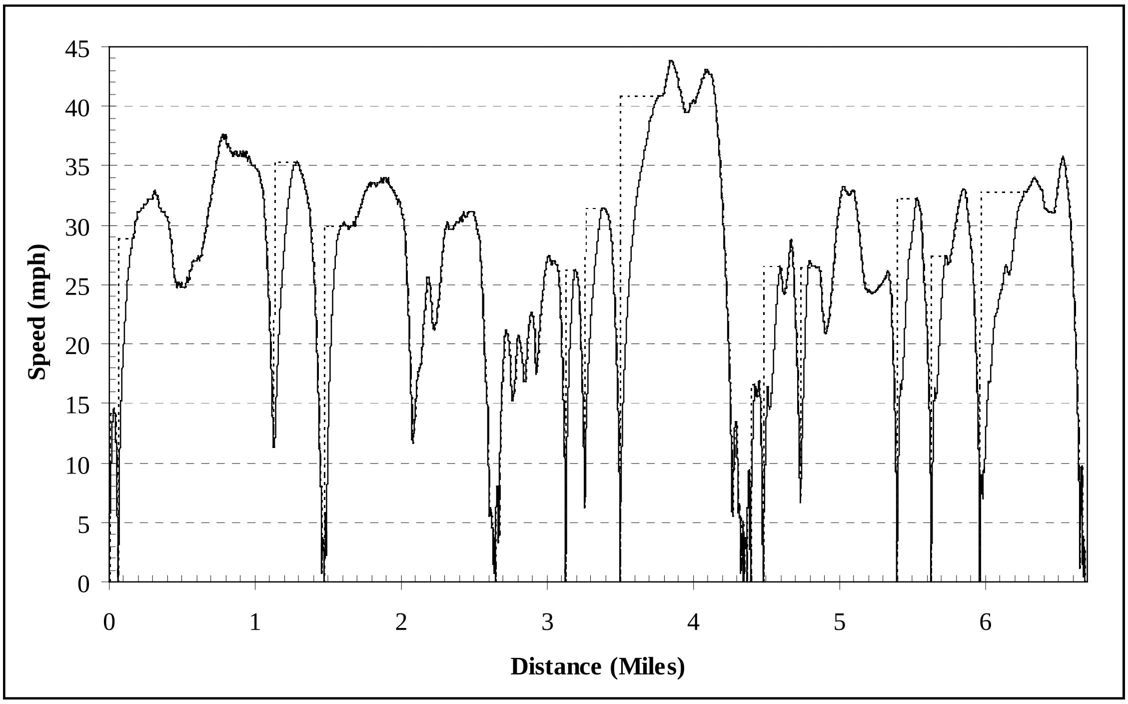


Table 3-1: Selected Statistics of Various Heavy-Duty Engine and Vehicle Driving Cycles

Cycle	Duration (sec)	Distance (miles)	Average Speed (mph)	Maximum Speed (mph)	Average (Absolute) Acceleration (mph/sec)	Maximum Acceleration (mph/sec)	Maximum Deceleration (mph/sec)	Idle Time (sec)
Federal HDGE Certification Cycle	1167	(see note 1)	(see note 2)	(see note 2)	(see note 2)	(see note 2)	(see note 2)	325
Federal HDDE Certification Cycle	1199	(see note 1)	(see note 2)	(see note 2)	(see note 2)	(see note 2)	(see note 2)	477
Alternate Federal HDGE Certification Cycle	1167	(see note 1)	(see note 2)	(see note 2)	(see note 2)	(see note 2)	(see note 2)	363
Federal Heavy Duty Chassis Cycle	1060	5.552	18.86	58	0.585	4.38	-4.63	338
New York Non-Freeway Segment of the Federal Chassis Cycle	254	0.5335	7.56	34	0.594	4.38	-4.18	127
Los Angeles Non-Freeway Segment of the Federal Chassis Cycle	285	1.1523	14.55	42	0.643	3.97	-4.18	79
Los Angeles Freeway Segment of the Federal Chassis Cycle	267	3.3327	44.94	58	0.505	2.95	-4.63	5
SAE J1376 Long Haul Cycle	(see note 3)	30	(see note 3)	55	(see note 3)	WOT	(see note 3)	180
SAE J1376 Short Haul Cycle	(see note 3)	7.5	(see note 3)	55	(see note 3)	WOT	(see note 3)	120
SAE J1376 Alternate Short Haul Cycle	(see note 3)	15	(see note 3)	55	(see note 3)	WOT	(see note 3)	240
SAE J1376 Local Test Cycle	(see note 3)	3	(see note 3)	35	(see note 3)	WOT	(see note 3)	300
SAE J1376 Alternate Local Test Cycle	(see note 3)	2	(see note 3)	30	(see note 3)	WOT	(see note 3)	720
SAE J1376 Transit Coach Design Operating Cycle (see note 4)	2830	14.0471	17.87	55	0.859	13.03	-4.58	670
CBD Segment of the SAE J1376 TCDOC (see note 4)	560	2.0247	13.02	20	1	2.56	-4.44	98
Arterial Segment of the SAE J1376 TCDOC (see note 4)	270	1.9838	26.45	40	1.185	4.58	-4.44	28
Commuter Segment of the SAE J1376 TCDOC (see note 4)	310	4.0051	46.51	55	0.355	13.03	-4.58	20
West Virginia University Truck CBD Cycle	854	2.1831	9.2	20	0.656	0.8	-1.4	159.6
West Virginia University Five Peak Cycle	850	5.0068	21.21	40	0.353	0.9	-1.4	104
West Virginia University Five Mile Route Cycle	(see note 5)	5.0068	(see note 5)	40	(see note 5)	WOT	-1.4	104
New York City Garbage Truck Cycle	585	0.3788	2.33	20	0.263	2.8	-1.4	404
New York CityBus Cycle	600	0.6148	3.69	30.8	0.662	6.2	-4.6	392
New York City Truck Cycle	1016	2.1343	7.56	34	0.594	4.4	-4.1	511.2
New York City Composite Cycle	1030	2.5053	8.76	36	0.699	4.63	-4.38	322
Heavy Duty Vehicle FTP Energy Conservation Cycle (see note 6)	1283	8.3122	23.34	68.33	0.589	5.15	-2.43	281
West Virginia University City/Suburban Heavy Vehicle Route Cycle	(see note 7)	6.6807	(see note 7)	43.8	(see note 7)	WOT	-4	386.5

Explanatory Notes:

1. Cycle distance statistics are not relevant for an engine-based cycle. Even if engine speeds were converted to vehicle speeds for a given vehicle/load combination, corresponding distance statistics would only be applicable to the specific vehicle/load combination as cycle absolute engine speeds vary across test engines.
2. Cycle engine speed and acceleration statistics vary in accordance with the rated speed of the test engine.
3. For distance-based cycles with wide-open throttle (WOT) accelerations, absolute cycle time duration, average speed, average acceleration, and maximum acceleration statistics are dependent on the available power of the test engine. Maximum deceleration statistics are indeterminate due to the combination of coastdown and braking decelerations in cycle definition and the dependency of the former on test vehicle mass.

4. The tabulated cycle statistics are based on a distance-limited interpretation of cycle accelerations. It is obvious that such an interpretation produces unrealistic maximum accelerations for both the Arterial and Commuter Sub-Cycles , but it should be recognised that the indicated maximums are of a single second duration and rapidly decline to more reasonable values. For the Arterial cycle, the acceleration values for the two seconds immediately following the indicated maximum are 2.57 and 2.13 mph/sec respectively. For the Commuter cycle, the corresponding values are 3.24 and 2.25 mph/sec. Therefore, any failure to keep pace with the indicated maximums will be of little consequence on overall cycle statistics. This problem arises from a failure of the SAE J1376 standard to adequately define the TCDOC as described in Section 2.2.2. An alternative linear-acceleration interpretation of the TCDOC will affect the tabulated cycle statistics as follows:

		TCDOC	CBD Sub-Cycle	Arterial Sub-Cycle	Commuter Sub-Cycle
Distance	(miles)	13.3486	2.0028	1.8444	3.6514
Average Speed	(mph)	16.98	12.88	24.59	42.40
Maximum Acceleration	(mph/sec)	2.00	2.00	1.38	0.61

5. The WVU Five Mile Route Cycle is a distance-based, WOT acceleration version of the WVU Five Peak Cycle. As such, absolute cycle time duration, average speed, average acceleration, and maximum acceleration statistics are dependent on the available power of the test engine. Corresponding statistics for the WVU Five Peak Cycle illustrate the design cycle values upon which the WVU Five Mile Route Cycle is based.

6. The FTP Energy Conservation Cycle is vehicle/load dependent and also requires a detailed shift, clutch, and braking schedule for proper administration. The tabulated statistics are for a 1990 Freightliner tractor with a 325 horsepower Caterpillar 3176 engine towing a 45 foot cargo trailer with a gross combined weight of 45,800 pounds and are intended only to be illustrative of this one particular cycle. Cycle statistics for other vehicle/load combinations will vary from the tabulated values.

7. The WVU City/Suburban Heavy Vehicle Route (CSHVR) is a distance-based, WOT acceleration cycle and as such, absolute cycle time duration, average speed, average acceleration, and maximum acceleration statistics are dependent on the available power of the test engine. Design cycle statistics for the uncertain parameters are as follows: cycle duration is 1700 secs (28.33 min); cycle average speed is 14.15 mph, cycle absolute average acceleration is 0.655 mph/sec, and cycle maximum acceleration is 2.60 mph/sec. Vehicles with more available power than the design vehicle will complete the cycle quicker, with higher average speeds and accelerations, whereas lower power vehicles will require more time and exhibit lower average speeds and accelerations.

While the various geometric cycles examined have definitive weaknesses relative to their ability to represent actual in use vehicle emission rates (no vehicles operate in the stylised modes comprising these cycles), the inclusion of one or more of these cycles in any future test program in Australia may be advantageous for two reasons. First, while the detailed cycle characteristics are certainly not reflective of real world operation, average cycle statistics may be reasonable approximations of aggregate real world behaviour. Second, use of one or more of these cycles will provide a potential linkage to in use emissions data collected in other test programs.

Geometric cycles dominate previous heavy-duty vehicle testing programs. In this regard, the SAE J1376 CBD Sub Cycle, the WVU Five Peak Cycle, the WVU Five Mile Route Cycle, the WVU Truck CBD Cycle, and the New York City Garbage Truck Cycle all have been used to support recent heavy-duty vehicle emissions test programs. Of these, the SAE J1376 CBD Sub Cycle appears to the most common link to multiple test programs (although as described in Section 2.2.2 above, required researcher interpretation during cycle implementation as well as WVU's demonstration of institution specific acceleration dependencies renders this linkage somewhat tenuous).

All of the various transient cycles presented are worthy of consideration. In most locations, the various New York City cycles would probably be inappropriate due to their very low speed distributions, but it may be useful for "inner city" simulation. Without question, the transient cycle that has been used most often in previous heavy-duty vehicle test programs is the Federal Chassis Cycle. While many of these programs erroneously assumed that the cycle was correlated to the federal engine certification cycle, they nevertheless collected in use emissions data using the chassis cycle. The New York Non-Freeway Sub Cycle of the Federal Chassis Cycle is an equally viable candidate. The major weakness of all these transient cycles is their speed versus time design basis, which is unlikely to accurately reflect the real world behaviour of vehicles with substantially different power-to-weight ratios. The WVU CSHVR Cycle is currently the only viable candidate cycle that overcomes this weakness, but its speed and acceleration performance characteristics are probably not reflective of the operational constraints imposed by New York City traffic.

Finally, the Heavy-Duty Vehicle FTP Energy Conservation Cycle approach is a viable candidate for testing program inclusion if correlation with the engine certification cycles can be demonstrated (which has not yet been accomplished). However, it would be beneficial to calculate emissions (should the cycle be selected for testing program inclusion) separately for the aggregate cycle and the portion of the cycle that corresponds to the portions of the engine certification cycle.

4 EMISSIONS CORRELATION BETWEEN DIFFERENT TESTS

4.1 ISSUES

There has been considerable interest recently between the emission correlations not only between different test procedures but also between engine dynamometer and chassis dynamometer based tests. The obvious area of interest for engine manufacturers has been correlation of 13-mode engine based test results with U.S. transient cycle engine based test results, and studies have been conducted in both the U.S. and Europe on this question. As noted in Section 3 of this report, correlation's between engine based steady-state test (mostly 13-mode) and chassis dynamometer based 13-mode test has been conducted almost exclusively in Europe with virtually no testing in the U.S. In contrast, correlation of engine dynamometer transient cycle emissions with chassis dynamometer transient cycle emissions has been conducted exclusively in the U.S. There has been some limited study of geometric cycles and their relationship to the certification transient cycle in Europe, and these connections have been established in studies in Germany.

The correlation issues raised by the comparisons are quite complex as there are many sources of variability that can affect the correlation between any pair of unique tests.

First, any given engine has some cycle-to-cycle variability even on a very accurate and reproducible test cycle conducted on an engine dynamometer. Although the level of variability cannot be separated from the measurement error of the emissions measuring instruments, most modern diesels are believed to have cycle-to-cycle variability of much less than five percent, and it is potentially in the two percent range for most pollutants.

Second, identical engines of a given engine family can have different emission due to different production tolerances in the emission critical parts. Engine-to-engine variability can be quite high, and the net emission distribution is often modelled as a lognormal or Weibull distribution. The coefficient of variation (σ/x) can be around 15 percent, so that engines at either end of the distribution can differ in emissions by a factor of two, or more. In this context, it should be noted that emission regulations do not require all engines to meet emission standards, but rather, it be established with a high level of confidence that the average emission are well below standards.

Measurement variability arises from random and systematic errors in the emissions measurement train. While guidelines for repeatability vary among laboratories, a typical COV for engine tests that includes engine variability is around three to five percent. Of course, instrument error is often defined at full scale and, at very low emission levels, COV can increase dramatically. This is particularly true for particulate measurements, where particulate is collected and weighed on a filter. Particulate weights of less than a milligram are difficult to measure accurately.

Driver variability is a separate issue that applies to chassis dynamometer tests. Drivers have to follow a cycle trace and shift the transmission at specific points, and the speed errors and shift errors can be significant. Trained and expert drivers can reduce the variability to levels approaching an engine dynamometer test, but even between expert drivers, there are differences in how "aggressively" the trace is followed. In addition, there can be significant error when specific engines or transmissions do not allow the driver to keep up with the driving trace even at full throttle. Such issues are, of course, relevant only for transient tests.

The significance of the above discussion arises when attempting to correlate results from a chassis dynamometer based test of a particular engine to the certification test result of an engine tested on an engine dynamometer. All of the above sources of variability are included, making the interpretation of results very difficult.

The following subsections discuss the correlation between (1) engine based 13-mode and transient tests, (2) chassis based 13-mode and engine based 13-mode tests and (3) between chassis based transient tests and engine based transient tests.

4.2 COMPARISON BETWEEN ENGINE BASED 13-MODE AND TRANSIENT TESTS

As noted earlier, diesel engine manufacturers did not wish to incur the expense of installing transient cycle dynamometers in the 1980s and U.S. manufacturers and European manufacturers attempted to develop correlations between the 13-mode test and the U.S. transient test. In each case, the same engine was tested on both cycles on the same laboratory, so that comparison errors were minimised.

In the early 1980s, approximately 50 engines were tested in the U.S. on both test procedures, but some of the data was not available publicly. EEA (1985) obtained data for 33 engines and estimated the relationship between steady state and transient emissions. It was discovered that Cummins engines behaved uniquely and differently from all other engine types due to their unique fuel systems. Hence the 15 Cummins engines and 18 "other" engines were separated into two groups for the regression analysis [5].

For the non-Cummins engines, EEA found that:

$$H_{CT} = \underset{(0.184)}{0.167} + 1.05\ HC_{SS} \qquad (r2 = 0.70)$$

$$NO_{xT} = \underset{(0.13)}{1.70} + 0.75\ NO_{xSS} \qquad (r2 = 0.82)$$

Where subscript T is for transient test and SS for steady state test.

For the Cummins engines, EEA found

$$HCT = \underset{(0.25)}{0.31} + 1.77\ HCSS \qquad (r2 = 0.79)$$

$$NOxT = \underset{(0.13)}{1.03} + 0.81\ NOxSS \qquad (r2 = 0.84)$$

While the NO_x relationships are similar, the HC relationships are quite different between the two groups of engines. Nevertheless, it is important to note that reasonable correlation was obtained between two very different test methods over a very broad range of emissions performance (HC ranging from 0.4 to 3 g/kWh and NO_x from 4.5 to 14 g/kWh on the transient test).

It is particularly significant that the correlation was obtained between two tests, one using a cold start and the other starting with an engine that is fully warmed up. Many in the industry believed that these correlations could be further improved by reweighting the different modes on the steady state test.

---

[5] Numbers in parentheses are standard errors of coefficients.

No data on particulates were available from the U.S. steady state tests, but EPA believed that the correlation between steady state and transient test particulate emissions is poor. Manufacturers advanced a number of engineering reasons that suggest it may be possible to obtain good correlations for all emissions of concern between steady state engine "maps" and transient cycle emissions because:

- Diesel engines do not require acceleration enrichment, and the air fuel ratio during a transient acceleration/deceleration is more carefully controlled than in a gasoline engine.
- Diesel engines require very little cold start enrichment, and the effect of cold starts on emissions is small.
- Diesel engines do not (yet) use any exhaust aftertreatment, and modelling their emissions do not, therefore, require the difficult prediction of catalyst efficiency.

European manufacturers have actively investigated the particulate question, and developed a particulate measurement system suited to the 13-mode test that did not require the weighting of 26 filters (two for each mode). Test results were obtained for 29 engines the spanned the range of 100 to 200 kW output (Cornetti et al:1988). Both linear and quadratic fits were attempted and the regression results are:

$$PM_T = 0.25 + 75\ PM_{SS} \qquad (r2 = 0.67)$$

and

$$PM_T = -0.10 + 2.04\ PM_{SS} - 1.04\ PM_{SS2} \qquad (r2 = 0.77)$$

The coefficients were significant at the 95 percent level, and the standard error of the estimate was 0.12 for the linear fit and 0.10 for the quadratic fit. However, visual observation of the data plotted in Figure 4-1 shows that one data point in particular (with relatively low transient cycle emissions but high steady-state emissions) is responsible for the quadratic fit, and the regression is not very robust.

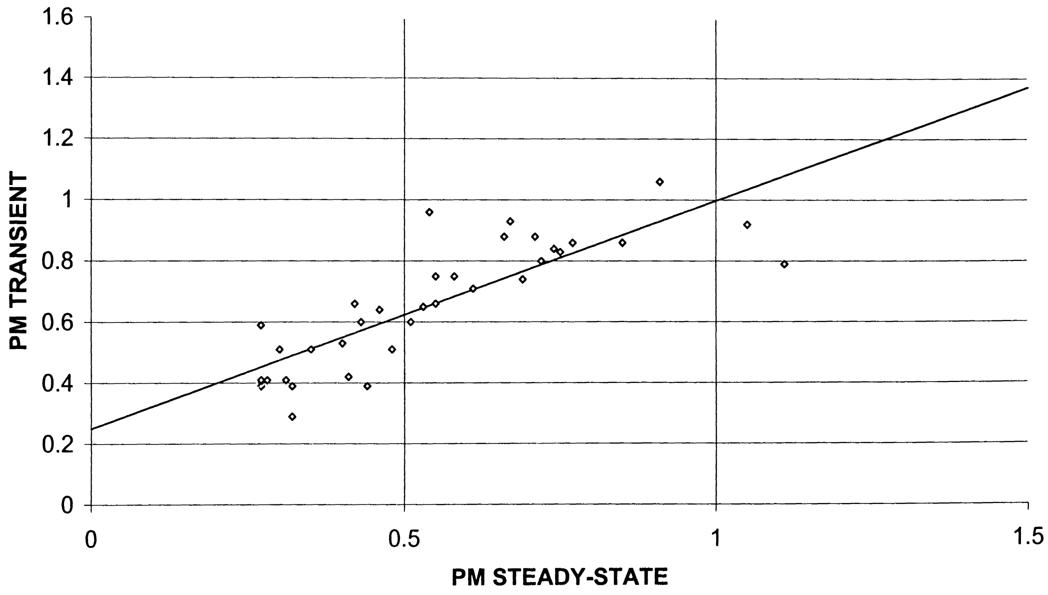
In both the NOx and PM regressions, the intercept term is quite large, and would invalidate any comparison at low NO_x or PM emission levels. For example, the US PM emission standard is now at 0.10 g/bhp-hr (0.13 g/kWh), which is less than half the intercept term in the PM equation. Hence there is now widespread acceptance of the fact that at low emission levels, there is little correlation between the two test procedures. Nevertheless, Australia could be interested in these correlations as they apply to older, higher emitting engines.

More recently, the TUV-Rheinland (1995) in Germany conducted emission factor testing on 34 engines certified to the Euro I, 88/77/EEC and R49 standards using both the U.S. transient test and the new European transient test. EEA obtained only aggregate data on emission averages by certification level for the two cycles. Emissions for all pollutants are higher on the European transient test, HC and PM by about 15 percent and NO_x by about six percent. The 13-mode R49 test had the highest NO_x level on average.

4.3 CORRELATION OF ENGINE BASED STEADY STATE TESTS TO CHASSIS BASED STEADY-STATE TESTS

The work on correlation between engine based tests and chassis dynamometer tests has been continuing since the early 1990s, and the original Van Gompel and Verbech (1993) publication on the "Diesel Controle Methode" (in Dutch) served as the basis for testing accuracy according to 88/77/EEC and 72/306/EEC.

Figure 4-1: Correlation of PM Emissions Measured by Transient and Steady-State Tests (g/bhp-hr)



Source: Cornetti et al (1988)

As noted in Section 3, the correlations' principal concern is the error associated with power measurement at each of the 13-modes, since RPM can be measured with great accuracy and steady- state emission measurements are not a significant source of error (typical measurement errors are less than one percent, unless the emission are at the threshold of the instrument sensitivity). PM emission measurement can have a COV of five percent or higher duet to the difficulty of measuring PM on the light loads of the 13- mode test.

The calculation of engine power delivered to the chassis dynamometer is obtained from the following equation:

$$P_{engine} = P_{wheel} + P_{trans} + P_{aux} + P_{roll}$$

where subscript:
- engine is the engine power output
- wheel is the measured power at the wheels
- trans is the power loss in the transmission
- aux is the power to auxiliary drivers
- roll is the rolling resistance loss

The 'Diesel Controle Methode' project10 recommended the formula:

$$P_{aux} = P_{rated} \times [0.0139 (n / nr) + 0.032 (n / nr)^3]$$

where: n is the test RPM

nr is the rated RPM

The formula is empirically derived and may not hold true for Australia. The project also derived detailed tyre rolling resistance power (Proll) as a function of tyre temperature and rolling resistance coefficient, while a similar empirical formula was derived for transmission loses. Since the first correlation project, two more recent projects have been conducted, one in 1994-1995 and one in 1996-1997. In the 1994/1995 project, five engine were tested on the engine and chassis based cycles, and the empirical power loss formulae were revised. In the most recent project, four additional engines were tested with some slight readjustment to the formulae to derive power losses (Rikjeboer et al:1998).

The power delivered can also be calculated on the basis of fuel consumption, if the engine brake specific fuel consumption is available at the test point or measured from the engine dynamometer. Results from the two methods to estimate engine power are compared in Table 4-1, using the formulas for power losses derived in the original study and the most recent updates.

It should be noted that the most recent update shows that the average error in calculated power has been reduced to less than 0.5 percent. The maximum positive error observed for any mode has been reduced from 10.2 percent using the 1992 formulae to 4.2 percent using the latest (1997) method, while the largest negative deviation is increased slightly from –2.9 percent using the 1992 formula, to –3.4 percent.

Table 4-1: Steady State 13-Mode Test Error in Power Loss Calculation

Engine Make	Model	1992* Method	1996* Update	1997* Update
1995 Tests				
DAF	RS108L	1.003	0.974	0.978
Mercedes	OM 366 LA	1.021	1	1.007
Renault	MIDR 06.35	1.018	0.984	0.991
Scania	DTC 1101	1.059	0.997	1.009
Volvo	D12A-380	1.076	1.016	1.029
Average		**1.035**	**0.994**	**1.003**
1996-1997 Tests				
DAF	RS222L	--	0.973	0.98
MAN	D 0826 LF08	--	0.995	0.999
Mercedes	OM 366A	--	1.033	1.03
Scania	DSC1201	--	0.975	0.988
Average			**0.993**	**1.001**

Source: Rijkeboer(1998)

* Values are ratios of engine power calculated using empirical formula versus power calculated using fuel consumption.

The deviations plus the error in measurement of emissions contributes to total error. The data presented imply that maximum error for all gaseous pollutants is less than six percent, while average error is probable in the range of ±2 percent.

The emissions data, however, showed larger variations than expected. EEA obtained data on six engines tested on both the engine and chassis tests, and the data are shown in Table 4-2. NOx emissions indicated an average error of ±4 percent but maximum error was almost ten percent.

PM variation was much higher, but this may be due to the low absolute values of PM emissions, in the range of 0.1 to 0.25 g/kWh. Typical absolute differences between chassis and engine-based measurements are on the order of ±0.02 g/kWh, which can result in an error of 20 percent. It appears that this relates to the error at measurement thresholds where measuring instrument errors rather than correlation issues also become important. However, it also indicates the problem of obtaining good correlation at low emission levels especially for PM.

Test correlation on the Japanese 13-mode was examined by the Japan Auto Research Institute (JARI), where four trucks were tested on both the engine and chassis based test procedures. EEA did not obtain the entire report (in Japanese) but obtained a translated executive summary. The results are largely consistent with the European experience, although the Japanese 13-mode test is defined differently. The correlation for all pollutants except PM was within ±5 percent, and was within ±10 percent for PM.

Table 4-2: Correlation of Emissions on 13-Mode Test

ENGINE MANUF.	ENGINE NOx	CHASSIS NOx	ENGINE HC	CHASSIS HC	ENGINE PM	CHASSIS PM
MAN 1	11.69	12.71	0.15	0.30	0.13	0.12
DAF 2	8.39	8.36	0.38	0.35	0.13	0.15
DAF3	9.01	9.23	0.47	0.32	0.13	0.13
VOLVO 1	11.51	11.15	0.35	0.32	0.13	0.14
SCANIA 1	13.27	13.00	0.72	0.67	0.19	0.17
SCANIA 3	12.32	12.73	0.71	0.76	0.21	0.23
MERCEDES	7.72	7.53	0.61	0.60	0.23	0.25

4.4 CORRELATIONS BETWEEN CHASSIS DYNAMOMETER AND ENGINE DYNAMOMETER TESTS: TRANSIENT EMISSIONS

The correlation of results between chassis and engine dynamometer based transient test emission has been the subject of substantial recent interest from the U.S. EPA and California Air Resource Board. However, such correlations are both difficult and expensive, in part due to the limited test facilities available. Hence, even to this day, the total number of actual comparisons of the same engine tested on the two different dynamometers is very small. The procedures are still under development, and the success of these efforts is by no means assured.

In the early 1980s, a relatively small number of in-use 1979 HDTs and buses (thirty) were tested by South West Research (SWRI). The HDTs were tested on a chassis dynamometer over a transient cycle test that was not exactly identical to the New York and L.A. urban cycles and the LA freeway cycle used to simulate the engine test. Nevertheless, the chassis test had similarities in average speed and loading to the engine test procedure.

Three of the engines in the vehicles were removed and tested on the engine test procedure, providing at least a reference for comparison of emissions from the two test procedures. Based on the fuel consumption data from the three engines tested on both procedures, EEA (1985) developed a method to calculate the work done, in kWh, for an engine driven over the chassis dynamometer cycle given the dynamometer settings of inertia weight and absorption horsepower. In two of the three cases, the match between emissions in g/kWh and g/km was extremely close, within ±5 percent. In the third case, the match was much poorer (+20%) due to the fact the vehicle was equipped with a high horsepower engine, which was very lightly loaded on the chassis dynamometer test but loaded normally on the engine test.

The fuel consumption based methodology can be simply derived from the conversion of g/kWh to g/km of vehicle travel, using the equation:

$$\text{g/km} = \text{g/kWh x kWh/km}$$

$$= \text{g/kWh} \times \frac{\text{kWh}}{\text{g-fuel}} \times \frac{\text{g-fuel}}{\text{km}}$$

The g-fuel/kWh is the engine brake specific fuel consumption (bsfc) and the term g-fuel/km is the vehicle fuel consumption. In the particular case of the SWRI tests both terms were available as measured quantities from the same engine but such data is not universally available for any random chassis test, so that typically on “official” or specification value must be used for bsfc.

The above equation is an identity that must hold true for all pollutants. Yet, on broader samples of vehicles using “official” bsfc values, the conversion factors were found to vary by pollutant. A 1992 U.S. EPA report suggested conversion factors (in bhp-hr/mile) ranging from 1.6 for HC to 4.3 for CO, indicating significant cycle specific variation.

Very little research was conducted from the mid-1980’s to the mid-1990s on this topic in the U.S. More recently, there have been three significant studies aimed at establishing correlations between the chassis and engine based transient cycles.

One analysis by the Colorado School of Mines (McCormick et al:1998) examined the correlation between the engine based U.S. FTP test and the U.S. Federal chassis cycle, for three heavy-duty engines, all of 1993 model year. The engine-based test included both cold and hot cycles, and involved three repeats of the hot cycle for each engine. In all cases, the measured THC emissions were very low; the two Detroit Diesel Series 50 engines had THC emissions below 0.05 g/bhp-hr or less than five percent of the applicable standard, while the Navistar DTA-466 has emissions of 0.16 g/bhp-hr, still substantially below standards.

As a result of the very low THC level, the coefficient of variation (COV) for the THC emissions measured was quite high, ranging from 16.5% for one DDC Series 50, to about six percent for the DTA-466. The COV for PM measurements was under seven percent, and less than one percent for NO_x, for all three engines on the engine test. All three engines easily met the emission standards for 1993. The chassis dynamometer tests also revealed very high levels of COV for three repeat tests for HC emissions. The COV was at 33 percent for one DDC Series 50, and at 20 percent for the other two engines. COV levels for NO_x on the chassis test was quite low, at less than four percent for all engines.

The comparison between engine and chassis based results can be best shown as the calculated conversion factor for each pollutant in bhp-hr/mile. Ideally, the conversion factor should be identical for all pollutants. However, the calculated conversion factors are relatively low for HC, and reasonably similar of PM, NO_x, and CO, as shown in Table 4-3.

Table 4-3: Calculated Conversion Factors – Engine to Chassis Dynamometer Results (bhp-hr/mile)

Test Number	1	2	3
Vehicle Type	Bus	Bus	Truck
Engine	DDC S50	DDC S50	DTA-466
THC	3.6	9.67	1.81
NO_x	7.27	5.32	2.78
CO	6.59	5.53	2.65
PM	6.83	7.63	3.85

Source: McCormick et al: 1998

For these latter three pollutants, the average conversion factor is 6.90 + 0.34 for the first engine, a COV of about five percent. For vehicle 2, it is 6.16 + 1.27, so that the COV is about 20 percent. For vehicle 3, the conversion factor is 3.09 + 0.66, so that the COV is about 22 percent. THC measurements are excluded from this analysis due to the very low emission levels where measurement instrument errors could be quite significant.

The 20 percent COV is broadly indicative of the type of correlation that is possible between the engine and chassis test for emissions when emission levels are not at measurement thresholds.

The reasons and sources for this error are discussed in Section 3, and it is largely because:

1. the engine test is scaled to the torque and RPM characteristics of the engine under test, whereas the driving cycle is invariant for all engines;

2. many parameters in the chassis test are not well specified and depend on individual laboratory practices or project specific practices.

A more recent study was funded by the California Air Resources Board (1998) and conducted by West Virginia to improve the chassis test procedures. The test program utilised two trucks a Navistar T 444 E engine in a six speed single axle International chassis truck, and a Cummins N14 engine in a ten speed over-the-road tractor that was configured to operate either with tandem driven axles or a single drive axle. Both engine and chassis emission tests were employed. Each engine was subjected to mapping and to hot and cold engine certification tests. The levels of carbon dioxide (CO2), CO, NO_x, HC, and (PM) were recorded. In addition, the engines were operated in various tampering modes to raise emission levels with a view to correlating these elevated levels with the behaviour when the engine was later tested on the chassis dynamometer. The Navistar was tested with an alternate stock controller and three temperature sensor tampering modes that caused the engine to employ a cold start mode and elevated NO_x levels. For example, with the sensor input falsely set to correspond to 39 degrees Fahrenheit (four degrees Centigrade), the hot test NO_x level was 15.25 g/bhp-hr (20.45 g/kWh)compared to 4.98 g/bhp-hr (5.2 g/kWh) for the stock case. The Cummins engine was also operated with a disabled manifold air pressure sensor and a false manifold air pressure sensor signal that raised the level the level of PM measured.

Each engine was installed in a truck, and emissions testing was conducted using the West Virginia University Transportable Heavy-Duty Emissions Testing Laboratory, which employs a full-scale exhaust dilution tunnel and analysers similar to those in the engine emissions certification test cell. Power was withdrawn directly from the vehicles hubs while the tyres ran on rollers. Axle torque was measured using torque cells in the driveline and power was absorbed using eddy current dynamometers installed on the laboratory chassis dynamometer test bed. Motoring was not possible, so that some deviation between the engine behaviour during the chassis and engine testing did occur. Each vehicle was mapped to yield a curve of full power axle torque, with one gear selected, though the engine speed range. The axle torque was referenced back to engine speed and was used to construct the target axle torque schedule during the subsequent emissions testing. Resulting data provided for the development of a drivetrain and rolling tyre loss model: efficiency was typically less than 80 percent. Emission levels were measured for both trucks using stock and tampering modes, and the tractor was operated in three different gears and with tandem and single axle drive.

The chassis test (in grams/axle-power hour) and the engine test (in grams per brake kWh) based NO_x levels correlated well, for both the Navistar and Cummins engines, for the combination of data from both engines. A regression of the data indicated:

$$\text{Engine } NO_x \text{ (g/bkWh)} = 0.775 \times \text{Chassis } NO_x \text{ (g/akWh)} \quad (r2 = 0.95)$$

The excellence of this correlation can be attributed to the near linearity of NO_x with respect to engine power. A good correlation between chassis and engine tests was also found for $NO_x/CO2$ ratios:

$$\text{Engine } NO_x/CO2 = 0.98 \times \text{Chassis } NO_x/CO2$$

Particulate matter was less well correlated, with the best fit as

$$\text{Engine PM (g/kWh)} = 0.776 \times \text{chassis PM (g/akWh)} \qquad (r2 = 0.39)$$

Particulate matter emissions are non-linear with respect to engine load and escalate significantly as full power operation is approached. Hence, throttle control differences between engine and chassis tests may have had a major effect on measured PM emissions, especially since PM emissions are also sensitive to the transient operation of turbocharged diesel engines.

WVU researchers believed that PM measurements are marred by dilution tunnel behaviour, where factors such as thermophoresis, soot deposition on the tunnel wall and wall deposit shedding lead to variations between runs. The variations of PM measurements of + 10 percent between certification laboratories using engine dynamometers during "round robin" tests are common. All of these factors appeared to have contributed to the poor PM correlation observed.

The results of the project indicate that the proposed test method is far too complex for a field test, and that significant improvements to evaluating PM emission were not realised (NO_x is much easier to predict, as discussed in Section 4-1).

As implied in Section 3, there are now new efforts by the U.S. EPA and WVU that are focusing on the "energy conservation cycle " as a possible means of improving the correlation. These efforts are still in the preliminary stages, and no data is publicly available to assess the improvements in correlation yet. However, data could become available within the next year.

A brief summary of the levels of correlation achievable when emissions are well above measurement thresholds is provided below.

Test type	Dyno type	Correlation error level
13 mode vs US transient	Engine dyno to Engine dyno	15 percent for HC, CO and NOx at euro 1 and 2 levels. Poor for pm and at low emissions levels
13-mode vs. 13-mode	Engine dyno to Chassis dyno	5 percent average for HC, CO and NOx. Within 0.02 g / kWh for PM
US transient to US transient	Engine dyno to Chassis dyno	Potentially around 20 percent for HC, CO and NOx if engine load is similar. Unknown for PM

5 METHODOLOGIES FOR TESTING IN AUSTRALIA

5.1 OVERVIEW

The analyses presented in Sections 3 and 4 provide a number of insights into the methodologies to establish a correlation between chassis dynamometer emissions tests and engine dynamometer emissions tests. The recommendations presented here combine the insights from earlier analyses as well as insights obtained by EEA in discussion with researchers in the field. The recommendations are presented in the context of the current situation in Australia, which has limited heavy-duty vehicle test facilities, as well as the recent development of an Australian heavy-duty vehicle driving cycle.

5.2 CYCLE SELECTION

As noted in Section 3, the three most important chassis based test cycles for consideration are:

- The steady-state 13-mode test
- The SAE J1376 CBD cycle
- The U.S. Federal cycle

The steady-state 13-mode test has a number of advantages. The test equipment is relatively low cost, as no inertia weight simulation is required and no CVS system with bag sampling is required for emission measurement. Since most heavy-duty diesels sold in Australia are sourced from Japan and Europe, replication of the certification test is possible with good relative accuracy, in principle.

The J1376 CBD cycle is one of the most widely used tests around the world historically and is relatively simple to perform. Its possible uses for Australia are (1) it is capable of providing modal emission data if emission are measured on a continuous basis and (2) it can permit comparisons of Australian data to worldwide data. The CBD cycle is of particular interest for bus emissions, which is often the focus of emission control activity.

The U.S. Federal chassis cycle or its modified versions, may be of future importance to Australia. This may be the only chassis test available that can provide reasonable estimates of emissions on the European or U.S. transient emissions cycle at the very stringent standards proposed for NOx and PM in the next decade. As Australia moves to standards such as Euro IV and Euro V in the future, the Federal cycle may be required to test these vehicles for compliance. However, there are significant aspects of the cycle and test procedure still under development. It is an option where Australia should monitor developments but not adopt the cycle immediately.

In this context, the Australian Driving cycle that is under development should be reviewed by international testing experts to identify significant areas of concern for implementation. Our involvement in heavy-duty testing and the review presented in Section 3 and 4 show that the implementation details can have a major effect on measured emissions and should not be left for ad hoc interpretation by the laboratories concerned. The details include:

- determination of test weight (inertia) and dynamometer power absorption unit settings;
- specification of gear shifts;
- speed trace allowable error;
- total distance allowable error;
- acceleration specifications for different vehicle power-to-weight ratios.

It is our understanding that such implementation details have not yet been developed by the NEPC, and should be addressed in the development effort.

5.3 EFFECT OF VEHICLE SIZE/WEIGHT

Broadly speaking, the above procedures have been utilised to test trucks over a very wide inertia weight range from 7,000 kg to 30,000+ kg. Hence, the specification of the cycle is not necessarily affected by vehicle weight and size although the size of the dynamometer is affected due to the need for twin-roller dynamometers for vehicles over 18,000 kg GVW with twin drive axles. In addition, the dilution air requirements increase in proportion to engine rated HP, so that the emissions measurement system flow rate capability is an issue for large vehicles or large engines.

While the above issues are obvious, there are secondary issues that can cause testing problems. First, the power-to-loaded weight ratio decreases as a function of truck size, and large trucks of over 20 tons GVW have great difficulty in following a driving trace with a high degree of transient behaviour, leading to significant speed and distance errors over a chassis cycle. Secondly, large trucks feature multi-speed gearboxes, and many transient cycles do not allow enough time in the trace for manually shifting a nine or ten-speed gearbox. In contrast, many lighter models especially around 3.5 to five tons GVW are equipped with automatic transmissions which are easier to use in following a transient driving cycle, but could cause problems in the 13-mode due to the potential inability to hold the same gear for some subset of modes, and due to potential difficulty in maintain torque converter loss constant during a particular mode.

Third, most of the smaller trucks in-use in Australia are sourced from Japan, so that there is some correlation between truck weight and test type. Methods developed for larger European sourced engines may not be applicable to smaller trucks.

5.4 EFFECT OF CERTIFICATION STANDARDS AND COUNTRY OF ORIGIN

During the 1980 to 1995 period, there have been significant differences in the stringency of emissions standards between the U.S., Europe and Japan. As discussed in Section 6 of this report, typical average emissions for a modern diesel engine design that is largely "uncontrolled" is about 11 to 12 g/kWh for NO_x and 0.5 to 0.6 g/kWh for PM based on the U.S. transient test. These are averages, with emissions distributed widely around these values. Hence, most engines were significantly below applicable standards prior to the Euro I standards. The pre-1999 Japanese standard, based on their own speed 13-mode test, is also believed to be not very stringent on NO_x, and most engines are well below certification limits.

If Australia intends to test pre-Euro I or pre-1999 Japanese diesels for compliance with the standards in the country of origin, it is anticipated that few vehicles will fail to comply, and most will be well below standards.

On the other hand, post-1994 U.S. engines certified to very stringent NO_x and PM standards will be difficult to test on the 13-mode, since measured PM on any contemplated 13-mode or steady state tests will be close to measurement thresholds. Hence, the levels of measurement error for PM may be unacceptable for well-maintained diesel engines calibrated to 1994+ U.S. emission standards.

Separately, the issue of the Japanese 6-mode test, which applied to all 1994 and earlier vehicles from 3.5 to 12 tons indicates that the need to develop expertise in the steady-state 6-mode cycle, if compliance issues for these vehicles are of interest in Australia. If compliance with original six-mode standards is not an issue, than the specific issues with the six-mode test may not need investigation.

With the introduction of Euro III standards in Europe and the further tightening of standards in 2004 in the U.S. and 2005 in Europe, Australian testing capabilities must improve significantly so that it is possible to run a complete transient cycle with inertia weight simulation. We are aware that simpler test facilities are likely to be used in the near term due to the lack of test facilities in Australia, but caution that the usefulness of these facilities will be time limited.

There are also some special issues on data availability to conduct correlation testing. The 13-mode test requires knowledge of the test RPM values that can be obtained from the type approval certificate in Europe. No such equivalent is available in the U.S. and it is not clear if the type approval details are publicly available for Japanese certification. Using the fuel consumption based power setting determination on the 13-mode test could also result in problems if the engine bsfc maps are not readily available; such maps are difficult to obtain for Australian models of U.S. or Japanese engines.

5.5 EFFECT OF AGE/STATE-OF-MAINTENANCE

Most of the difficulties encountered with testing older vehicles are operational in nature. First, many older vehicles can be in poor mechanical state, and tyre and axle bearing failures can occur driving the test, causing damage or safety problems. Most facilities perform a detailed mechanical check of the drivetrain, brakes and tyres prior to acceptance for testing to ensure mechanical safety. Tyres are especially prone to damage at high load test points on the chassis dynamometer, and older vehicles must have good tyres, or else test tyres must be fitted to the vehicle.

Second, the availability of all required data to conduct the test may be a problem on older vehicles, especially if the engine sticker is missing or contains ambiguous data. Even in Europe, recent test programs on older trucks had difficulty in resolving engine certification states on about five percent of all trucks. The problem may be far more severe in Australia where there were no emission requirements prior to 1996.

Third, the fuel consumption based method may not yield correct results if the engine calibration is incorrectly set (either intentionally or due to component wear). For example, turbocharger wear would result in lower boost pressure at a given RPM/throttle setting, leading to significantly lower power than calculated based on fuel consumption. Hence, on test cycles such as the 13-mode where engine output must be estimated, the problems with older or mal-maintained engines could give rise to significant emission measurement errors if emissions are measured in g/kWh.

5.6 LEVELS OF CORRELATION ACHIEVABLE

The issues regarding correlation of emission measurements are relatively complex, and depend on the type of chassis test employed, the type and age of the vehicle tested, and the experience and expertise of the laboratory conducting the tests.

Successful correlation of chassis test based emission results with engine test based emission results have been achieved on the 13-mode test in Europe. Average emission error relative to the official certification test should be within ±5 percent but maximum error can be much larger especially for low emissions engines.

However, it should be noted that these tests have access to the type approval certificate that specifies engine RPM and fuel consumption at the different test modes. It also relies on the use of special tyres with known (measured) rolling resistance coefficients and empirical formulae derived for accessory and transmission power losses for European trucks. Since Australian diesel engines are sourced from a variety of countries, it is not clear that all of the required data inputs are available to achieve this level of correlation. In the more general case where the data inputs must rely on a combination of available data and engineering analyses, the correlation could be significantly worse.

In addition, there will be an initial phase where new laboratories in Australia will gain experience with the procedure. It is likely that once some experience is gained, a COV of ten percent maybe a reasonable expectation for correlation, for all pollutants except PM. For PM, the COV may be larger. However, for all pollutants, the COV will increase for tests on modern engines with very low emission levels.

Repeat tests of the 13-mode or any transient cycle on the chassis dynamometer should achieve a repeatability level with a COV of five percent or less for all pollutants except PM. The absolute emission level of PM and the repeatability of the PM measurement system may lead to higher variances, in the range of 20 percent.

Geometric cycles that can be used to generate modal data are typically very repeatable, and inter-lab comparisons have shown that cycle emissions can be reproduced with a COV of five percent or less, except in the case of PM emissions. Data from modal emissions profiles can be utilised to estimate emission factors for any driving condition.

"Realistic" driving cycles such as the chassis based U.S. transient test or the Australian Driving Cycle have a number of open issues regarding cycle specifications and test protocol that make it difficult to provide an estimate of correlation. If the cycle is defined as a speed/time trace that is invariant for all trucks, correlation with engine tests can be very poor. New developments to scale cycle characteristics to truck capability and to define testing protocol more carefully may lead to significant improvements in the correlation between measured emission on the chassis test and the engine test in the near future, but success is not assured. Data from limited testing suggests that a COV of 20 percent or so may be possible with well-specified test procedures.

5.7 CHECKLIST OF KEY ISSUES FOR TESTING

Based on recent considerations of the types of laboratories available in Australia, the NEPC could utilise the following points as a checklist for deciding testing capability.

- Dynamometer configuration – a twin roll dynamometer with inertia weights and a power absorption unit capable of simulating loads up to 300 HP and weights to 40,000 kg can be used for all types of tests. Axle or hub attached dynamometers can be used for steady state tests. If these dynamometers are not capable of motoring the engine during decelerations, emissions measured on transient tests may not be accurate, especially for PM and HC emissions.
- Emission measurement – gaseous emissions measurement is generally not a major problem. Measurement of PM emissions using a flow splitter/dilution tunnel approach is difficult for low PM emissions engines. Flow rates in the tunnel and filter weight measurement thresholds should be carefully considered for accuracy.
- Steady-state tests – reproduction of the 13-mode requires the ability to measure power output of the engine. If the power loss method is proposed, special tyres with known rolling resistance will need to be used. The adequacy of European formulae to predict transmission and axle power loss should be checked for a sample of Australian trucks. If fuel consumption is used as a power indicator, the availability of fuel consumption maps for tested engines from the manufacturer is essential.
- Transient cycle – detailed specifications need to be developed for all transient cycles including the CUEDC to enable correct setting of (1) inertia weight (2) power absorption (3) allowable speed trace error (4) allowable total distance error and (5) gear shift requirements

for any arbitrary transmission. Driver training will be required to follow the specified cycle trace with any arbitrary engine/transmission. Cycles will need to be “scaled” to each truck’s power-to-weight ratio.

- Country of origin of test truck – a comprehensive library of the type approval certificates will be required to determine the steady-state test modes for all engines. No such data is available on Japanese engines certified on the 6-mode test or U.S. engines certified since 1984. An alternative 13-mode test specification must be derived for such engines
- Older/Poorly maintained vehicles – apart from the usual safety issues, such vehicles may pose problems if 13-mode test power determination is fuel consumption based. Mal-performance in the engine can raise (or even lower) fuel consumption by as much as ten percent for a given setting. Hence, some procedure must be specified to determine the state of tune of a tested engine.

The levels of correlation achievable relative to an engine test are dependent on a detailed and successful resolution of all the issues raised above.

6 EMISSIONS DETERIORATION UNDER IN-SERVICE CONDITIONS

6.1 OVERVIEW

Project 6 as defined by the NEPC requires an examination of the emissions deterioration of both light and heavy-duty diesel vehicles under in-service conditions. However, the diesel fleet in Australia has few “light-duty” vehicles if one uses consistent definitions across countries. Diesel penetration in cars is very low, in the order of 2.5 percent, in Australia. Light commercial vehicles are not consistently defined in all the Australian states, but the broadest definition included passenger and cargo vans, sport utility (4 wheel drive) vehicles, small pickup trucks, as well as small delivery trucks in the 2.5 to 3.5 ton GVM range. Reports for the NEPC have identified the diesel penetration for the LCV fleet to be over 20 percent, but this may apply to a more narrow definition of LCV. For example, VFACTS reported sales of about 166,000 LCVs in 1997, of which small cargo vans were 20,000, pickup trucks were about 73,000, sport utility vehicles were about 71,000 and small commercial trucks were about 2000. Other LCV definitions do not include the sport utility vehicles, and we believe that the diesel penetration for LCV relies on this type of definition, and indicates sales of about 20,000 diesel LCVs per year in the recent past.

Typical diesel engines used in LCVs fall largely into two categories. One category includes smaller versions of heavy-duty engines used in vehicles in the 3.5 to 7 ton GVM range, such as a four cylinder version of a 6 litre displacement, 6 cylinder engine. This type of engine is popular for the 2.5 to 3.5 ton GVM class and in some pickup style vehicles and cargo vans. The second type are unique prechamber diesels that are relatively large displacement (about 4 litres) light duty engines. Such engines are used in several popular sport utility vehicles and pickup trucks, such as the Toyota Land Cruiser and Nissan Patrol. The emission characteristics of the first type are likely to be quite similar to the larger versions employed in heavy-duty trucks. The emission characteristics of the second group are largely unknown as no studies have been done of their in-use emissions. More conventional light-duty passenger car diesels have been largely of European origin, with VW, Mercedes and Peugeot accounting for the majority of such vehicles in Australia. There are few European studies of their emissions behaviour. Hence the focus of this report is on heavy-duty diesels, as this is most relevant to Australia.

The emissions of in-service heavy-duty diesel engines relative to certification levels have also not been studied extensively due to two reasons. First, diesel engine test facilities are quite limited and no good chassis test procedures exist, as is evident from the discussion in Sections 3 and 4. Second, diesel engines were widely believed to have stable emissions over their useful life; the U.S. EPA assumed emission factors essentially equal to certification standards, as an example.

Since the late-1980s, there has been a growing realisation that in-service diesels do not maintain certification level emissions over their useful life. There are several components to the in-service emissions deterioration, or “excess” emissions that occurs. First, even in the certification process, emissions are assigned a deterioration factor based on an idealised durability cycle, and the real world duty cycles imparts somewhat larger deterioration in emissions relative to the certification durability test. Second, the levels of maintenance recommended by the manufacturers are usually not strictly followed, causing additional deterioration. Third, there may be mal-maintenance (either intentional or unintentional) due to mechanic inexperience. Fourth, there may be intentional tampering, usually to increase horsepower or fuel economy. Lastly, there may be design defects in the emission control system that cause high emissions.

In general, the severity of the emission deterioration increases from the first reason to the fifth. However, tampering and design defects usually affect only a small portion of the fleet, except in some usual circumstances. Such a circumstance occurred recently in the U.S., where the EPA determined that heavy-duty engine manufacturers had employed 'cycle beating' devices that resulted in low certification test emissions but high in-service emissions.

The typical methodology used to determine the in-service emissions of a group or class of vehicles is to obtain a random sample of these vehicles that is a snapshot of their representation in the fleet and test them for emissions. The emission results are regressed against odometer (VKT) or vintage to obtain an average deterioration rate for the fleet. This method only works if the sample size is relatively large and the incidents of mal-maintenance and tampering in the sample are similar to the fleet wide rate. Typically, sample sizes of several hundred vehicles are necessary to capture those incidents (which occur at rates of a few percent, typically) and to provide reasonable confidence in the estimates.

Unfortunately, in the case of heavy-duty trucks, the samples range from a few vehicles to a few tens of vehicles, making statistical approaches of limited value. Hence, there have been attempts to model the emission deterioration on a semi-theoretical basis, using observed rates of mal-performance and tampering from larger samples with engineering estimates of the effects of the these defects on emissions.

Both the test data based approach and the modelling approach are described here, with the results compared.

6.2 EUROPEAN EMISSION FACTOR PROGRAMS

Significant testing in-service heavy-duty trucks has been conducted in Europe by two organisations in particular: the TNO in Netherlands, the Transportation Research Laboratory in the U.K. and TUV-Rheinland in Germany. More limited testing of trucks has been conducted in Sweden.

6.2.1 *Testing in Netherlands*

The TNO in Netherlands has conducted tests on the largest sample of heavy-duty trucks in Europe. Data from a November 1998 report19 indicates that total of 128 heavy-duty vehicles had been tested through early 1998, with the sample broken out as follows:

- 88/77EEC standard - 26
- Euro I standard - 76
- Euro II standard - 26

Virtually all of these trucks were tested on the R49 based 13-mode test conducted on a chassis dynamometer.

As noted in the discussion in Section 2 that Euro O (88/77/EEC) and Euro I standards were not very stringent, and most engines were certified at levels well below applicable standards. Hence, the prospect of failing the standards is quite unlikely, as it would require significant tampering.

For the 26 Euro O certification vehicles, there were no failures of NO_x or HC standards (No PM standards were in force). The highest observed NO_x was 10.2 g/kWh, which is well below the 14.4 g/kWh standard. Average levels for most engines were in the 7 to 8 g/kWh range with the lowest at 5.6 g/kWh. Typical PM level were 0.4 to 0.6 g/kWh, with the highest at 0.8 g/kWh.

Data on 64 of the 76 Euro I vehicles tested was available. There were several engines close to the 9 g/kWh production standard, and since measurement error and production tolerances can cause minor exceedances of the standard, we evaluated emission failures at a level about ten percent above the standards. Only four of the 64 engines exceeded the 10 g/kWh NO_x level, and three of the 64 exceeded the 0.44 g/kWh PM level. The highest observed NO_x level was 14.2 g/kWh and the highest PM level was 0.6 g/kWh.

Data on the 26 Euro II certification vehicles showed one vehicle with NO_x higher than ten percent above the certification limit of 7.0 g/kWh (i.e., over 7.7 g/kWh) and two vehicles exceeding the 0.15 g/kWh PM standard by over ten percent.

Both the Euro I and Euro II standard samples indicate a failure rate for each pollutant in the range of five to eight percent. Conversations with TNO indicated that is about the correct observed failure rate in Europe. It should be noted that few vehicles fail both NO_x and PM standards simultaneously.

The TNO also conducted detailed checks on a subset of engines were checked for calibration. The defects found and the observed rates are as follows:

- Incorrect maximum fuel setting - 11 percent
- Incorrect governor RPM setting - 5.5 percent
- Injection timing (early) - 8 percent
- Injection timing (late) - 13 percent
- Injector worn - 13 percent

Typically, early injection timing leads to high NO_x, while injector wear and incorrect fuel pump settings can lead to high PM and HC, if severe enough.

6.2.2 *Testing in the U.K.*

The Transportation Research Laboratory (TRL) conducted tests in 1998/1999 on 20 heavy-duty vehicles, ten of which were certified to Euro I standards and ten to Euro II standards. All vehicles were tested on a chassis dynamometer on both the 13-mode test and the European FIGE transient test. Fourteen vehicles had inertia weights between 12,500 and 15,000 kg, while six were lighter with the lightest at 5800 kg.

Consistent with the experience of the other European countries, only one vehicle of ten failed the Euro I standards, with NO_x emissions at 11.5 g/kW-h. None of these vehicles exceeded the HC, CO or PM standards. Similarly, only one of the ten vehicles failed the Euro II standard, with NO_x emission at 7.98 g/kW-h, while a second exceeded the NO_x standards by a small amount (two percent) so that it cannot be classified as a failure with high confidence.

Mean emission levels for the two groups of vehicles are as follows:

Euro I	-	0.43 HC/1.34 CO/7.45 NO_x/0.09 PM g/kW-h
Euro II	-	0.30 HC/1.60 CO/6.37 NO_x/0.05 PM g/kW-h

This shows that most Euro I engines were well below applicable production standards for all pollutants. The Euro II engine mean NO_x emissions were relatively close to standards, but all other pollutant emissions were well below standards.

The same engines tested on the FIGE transient cycle had NO_x emission that was about five percent lower on average, but HC emissions that were 30 percent higher, relative to the 13-mode test. PM emissions on the FIGE cycle were 0.24 g/kW-h for Euro I engines and 0.17 g/kW-h for Euro II engines. These values are much higher than those on the 13-mode test but still quite low in comparison even to Euro III standards.

6.2.3 *Testing in Germany*

The TUV-Rheinland has also tested a variety of engines, although there is no recent report on their test activities. One major emission factor program conducted in 1995 tested 34 engines9 with the sample breakdown as follows:

- ECE R49 - 20
- 88/77/EEC - 12
- Euro I - 2

In contrast to the TNO tests, the TUV tests were performed on an engine dynamometer. In addition to the 13-mode test, the U.S. transient test and a more detailed mapping of emissions at 35 steady-state test points were performed to develop a modal emissions model.

As expected, none of the engines exceeded the ECE R49-01 standards for NO_x and CO, although there were two engines with very high gaseous HC emissions and particulate emissions. The average HC emissions was 1.8 g/kWh, but the two 'high" engines exceeded 4 g/kWh. Average NO_x emission was 11.2 g/kWh, while the highest was at 17.3 g/kWh, slightly below the 18.0 standard. The two "high" HC emitters also had very high particulate emissions at over three times the average of 0.7 g/kWh.

The 88/77/EEC certified (Euro O) engines showed significantly lower emissions. HC and CO emissions were far below standards but one of the 12 engines tested exceeded the NO_x emissions standard of 14.4 g/kWh by less than ten percent. Particulate emissions were in the same range as in the TNO tests, but all engines had PM emissions below 0.6 g/kWh. The NO_x failure rate is statistically similar to the observed failure rate in the TNO tests.

The two Euro I certified engines were relatively new at the time of testing and had NO_x emissions of about 7 g/kWh and PM emissions of 0.3 g/kWh. HC and CO levels were at less than half the applicable standards.

6.2.4 *Other Tests*

Sweden has also recently conducted some testing of heavy-duty vehicles by its Motor Test Centre (MTC: the Swedish testing organisation) but the sample is very small. MTC has tested five heavy-duty trucks and two truck engines on the chassis and engine dynamometer respectively (MTC:1995). Sweden had optional certification to Euro II standards even prior to 1996 and two of the vehicles tested had apparently been certified to this optional standard. All vehicles met Euro I limits, but the two vehicles certified to the Euro II limits exceed the PM standard by small amounts. One vehicle tested was a Scania bus with an oxidation catalyst. It was tested twice, once when new and the second time at 142,000 km. Although there were emission increases with use, the absolute values of CO and HC emissions were very low (well below Euro II standards) due to the catalyst. The Swedish data has too small a sample to make broad judgements about emission failure rates or in-use deterioration in Sweden.

6.2.5 *Light-Duty Diesel Testing*

There have been tests of in-use light duty diesels by the TNO in Netherlands and by the TUV in Germany as part of broader emission factor programs for all light duty vehicles in the 1980s, but the overall sample of diesel vehicles tested in that era is still quite small. However, the issue with the European testing is that emission standards for light duty vehicles prior to the Euro I standard introduced in 1992 were quite lax, and the standards were above the near uncontrolled rate for light duty diesel vehicles for HC, CO and NOx. (Typically, HC and CO emissions from light duty diesels are at extremely low levels in comparison to gasoline engine emissions). There were no particulate emission requirements in the 1980s, and it was broadly concluded that emissions from in-use diesels did not suggest any large-scale violations of standards. The Euro I standard of 1992 imposed a HC+NOx standard of 0.97 g/km and a PM standard of 0.14 g/km while the Euro II standard of 1996 resulted in further reductions to 0.7 g/km and 0.08 g/km respectively. Even the Euro I standard for HC+NOx is still above the near uncontrolled emission level for most modern light-duty diesels and only the PM standard was a serious constraint. A testing program conducted during 1995-1997 in support of an Inspection test development program tested 28 diesels certified to Euro I levels. Not surprisingly, no vehicles failed to meet the standards for gaseous pollutants. Several vehicles failed to meet particulate emission standards, although only 3 of 28 vehicles exceeded the limit by more than 25 percent. Only one of the 28 vehicles was a “gross” emitter with PM emissions slightly in excess of 1 g/km, over 7 times the standard. As a result, much of the focus in Europe is on identifying and repairing high PM emitters.

6.3 EMISSION FACTOR TESTING IN THE U.S.

There has been remarkably little testing in the U.S. on broad samples of in-use trucks. A relatively small number of in-use diesel 1979 HDTs and buses (thirty) were tested by South West Research (SWRI) in the early 1980’s. The HDTs were tested on a chassis dynamometer over a transient cycle test that was not exactly identical to the New York and L.A. urban cycles and the LA freeway cycle used to simulate the engine test. Nevertheless, the chassis test had similarities in average speed and loading to the engine test procedure. The tests covered 23 heavy-duty trucks and seven buses.

A comprehensive analysis of the dependence of emissions on odometer from the chassis dynamometer data was attempted by converting the emissions to units of g/bhp-hr using a calculation derived from the dynamometer HP and weight setting (EEA:1985). It was obvious that the emissions (in g/kWh) were radically different for buses in comparison to trucks, and were typically two to three times higher on average. Therefore, it was decided to treat the two vehicle types separately. For the 23 trucks, inspection of the emission data revealed that there was a strong trade-off between HC and NO_x emissions. This trade-off is well known in engineering circles, and since the 1979 emissions requirements specified only a HC + NO_x standard, manufacturers often set different goals for HC and NO_x. Only one vehicle had both very high NO_x and very high HC emissions, and was removed from the analysis.

The remaining emissions data on 22 trucks were then analysed to provide emission factors as a function of use, i.e., a zero mile rate and an odometer dependent rate of the form:

Brake-Specific Emissions = C + D x ODOMETER

The results for HC, CO, NO_x, particulates and HC + NO_x are summarised in Table 6-1. Using data on the 22 trucks, it can be seen the odometer dependence of the emission factor (i.e. deterioration rate) is not statistically significant at the 90 percent confidence level for HC, NO_x

and HC + NO_x emissions. On the other hand, the deterioration rate for the CO and particulate emission factors are significant at the 90 and 95 percent confidence level, respectively.

Table 6-1: Results of Emission Factor Analysis (g/bhp-hr)

Emission	Intercept	Std. Error of Intercept	Deterioration Rate*	Std. Error of D.R.	Sample Mean
All 22 Trucks					
HC	0.765	0.125	$2.73x10^{-3}$ [b/]	$8.7x10^{-3}$	0.798
CO	1.954	0.652	$8.35x10^{-2}$ [c/]	$4.55x10^{-2}$	2.971
NO_x	7.131	0.521	$-5.59x10^{3}$ [b/]	$3.64x10^{-2}$	7.064
Particulate	0.475	0.081	$1.36x10^{-2}$ [a/]	$5.70x10^{-3}$	0.64
HC + NO_x	7.897	0.477	$-2.86x10^{-3}$ [b/]	$3.33x10^{-3}$	7.862
Cummins Only (12)					
HC	0.732	0.081	$1.850x10^{-2}$ [c/]	$1.22x10^{-6}$	0.94
CO	1.555	0.753	$1.721x10^{-1}$ [a/]	$5.60x10^{-2}$	3.492
NO_x	7.146	0.552	$-2.950x10^{-2}$ [b/]	$4.10x10^{-2}$	6.814
Particulate	0.397	0.089	$2.133x10^{-2}$ [a/]	$6.60x10^{-3}$	0.637
HC + NO_x	7.878	0.494	$-1.102x10^{-2}$ [b/]	$3.67x10^{-2}$	7.754
All Other Trucks (10)					
HC	0.75	0.083	$-9.232x10^{-3}$ [b/]	$5.50x10^{-3}$	0.628
CO	2.249	0.825	$7.171x10^{-3}$ [b/]	$5.40x10^{-2}$	2.315
NO_x	7.216	1.007	$1.106x10^{-2}$ [b/]	$6.59x10^{-2}$	7.363
Particulate	0.577	0.148	$5.071x10^{-3}$ [b/]	$9.70x10^{-3}$	0.644
HC + NO_x	7.966	0.972	$1.828x10^{-3}$ [b/]	$6.36x10^{-2}$	7.991

Source: EEA (1985) .

* In gm/BHP-hr/10^4 miles.

a/ Significant at the 0.05 level.

b/ Not significant at the 0.10 level.

c/ Significant at the 0.10 level.

Note: analysis results reported in g/bhp-hr units

The number of Cummins engines tested was the largest of any manufacturer, and all engines were of the same displacement (855 CID) but had different horsepower ratings.

Because of the physical similarity of the engines, EEA was of the opinion that a regression of emissions from these engines against odometer readings might provide a better indicator of the deterioration factors. Regression analysis of the data from 12 Cummins engines showed large improvements in the significance of the zero-mile and deterioration rate (d.r.) rate for all pollutants except the d.r. for NO_x. The values of the zero-mile emissions rate from Cummins engines did not show any significant differences from those for all trucks; however the deterioration rate for HC emissions was significant at 90 percent confidence, while the deterioration rates for CO and particulate were significant at 95 percent confidence.

As expected, regression analysis of the data from all “non-Cummins” engines resulted in loss of significance for all of the deterioration rate estimates. This is because of the wide range of manufacturers and engine sizes in the sample of 10 trucks. The results of the analysis of Cummins and non-Cummins powered vehicles are also shown in Table 6-1. Data from Cummins engines indicates that HC emissions increase by 72 percent [6] relative to zero mile emissions at the end of the engine’s useful life of 285,000 miles, while particulate emissions increase by 153 percent. The Cummins engines display high deterioration rates for particulate emissions relative to the overall average deterioration for all engines of 82 percent, partly because of low zero-mile emissions.

The emission estimates from the brake-specific emission analysis were compared with the only other source of equivalent data on heavy-duty diesel emissions. SWRI had previously tested 19 new engines on engine dynamometer tests to provide a 1979 baseline emissions value. The results of those tests of new engines are compared with the estimated zero mile emissions (i.e., intercept) from the chassis test data, in Table 6-2. The comparison shows remarkable agreement between the two values for all pollutants, especially considering the differences in test procedures employed. For all pollutants, the engine test based averages were within one standard error of the chassis test based averages.

Table 6-2: Comparison of 1979 Baseline Emissions with Intercept of Emission Factors (g/bhp-Hr)

Emission	Baseline (Engine Test)	Intercept (Chassis Test)
HC	0.83	0.765 ± 0.125
CO	2.28	1.954 ± 0.652
NO_x	7.04	7.131 ± 0.521
Particulate	0.49	0.475 ± 0.081

Source: EEA (1985).
Note: analysis results reported in g/bhp-hr

Bus emission factors did not show significant deterioration rates because the sample tested (seven) was too small for meaningful analysis but it should be noted that average bus emissions were a factor of two higher for all pollutants relative to truck emissions. This is usually ascribed to the very high accessory loads for bus engines

There have been no other structured emission factor type programs conducted on heavy-duty diesel trucks. West Virginia University (WVU) has tested over 100 vehicles, but the large majority of these tests have been on new or prototype CNG vehicles, or on diesel vehicles using JET A or biodiesel. In addition, most tests have been conducted on the WVU ‘Five Peak’Driving cycle so that results cannot be translated to emission factors easily. There has also been a large number of tests on urban buses, and data from over 120 tests are available. However, these buses are largely from New York City, and most were tested on the New York “Garbage Truck’ Cycle described in Section 3. In general, these emission rates tend to be three to four times as high as emissions form trucks tested on the EPA urban cycle.

[6] The percentages can be calculated from the deterioration rate and intercept in Table 6-1 as follows for HC: 0.0185 * 28.5/0.732.

There has been virtually no emission factor of light duty diesels in the US, largely because of very low light-duty diesel penetration in the US market. Diesels enjoyed a brief burst of popularity in the US light-duty market in the 1979 to 1983 time frame, with the GM 5.7 litre V8 diesel and the VW 1.6 litre 4-cylinder diesel accounting for the vast majority of sales. These first generation passenger car diesels suffered from several mechanical problems, with the GM diesel ,in particular, having such severe problems that it was withdrawn from production. A small number of these diesels were tested by the EPA and California in the mid-1980s and found to have high particulate and HC emissions, but these conclusions are probably specific to these models, and not generally applicable to better established diesels from Mercedes or Peugeot. Since that time, there has been no emission factor testing of light duty diesels in the US

6.4 HDDV EMISSION FACTORS DERIVED FROM MODELS

Due to the very limited testing of in-use HDDVs, the U.S. EPA has largely assumed the emission factors from certification standards. MOBILE5, the EPA Mobile Source emission inventory model incorporates emission factors for all HDDV's but treats all HDDVs as a single group, so that differences between light-heavy, medium-heavy and heavy-heavy duty vehicles cannot be observed from the emission factors. More importantly, the emission factors for HC and NO_x are based solely on certification standards and have zero deterioration rates for all diesel trucks since 1984. While detailed documentation of the EPA emission factor derivation was not provided, it is apparent that the emission factor is set approximately equal to an assumed certification level, which is 20 to 30 percent below the certification standard, for 1984 and later HDDVs. The U.S. EPA does not have separate emission factors for buses, and the available data suggests that bus emissions are significantly higher than truck emissions.

Surveys conducted by California have established that diesel truck HC emissions increase with use due to component deterioration, mal-maintenance or intentional maladjustment (tampering) in the field. Many types of mal-performances give rise to high smoke levels, and smoky trucks are widely observed on-the-road. Random samples of HDDVs from surveys conducted in 1990/1991 have indicated that about one-third of the HDDV population had smoke well in excess of certification standards, especially during acceleration. Hence, EPA's assumption of zero deterioration seems unjustifiable for HC and particulate emissions. However, the inverse relationship between NO_x and HC suggest that NO_x emissions deterioration with age or use may be zero or even negative.

Surveys of diesel engines in the field, and the expertise of the manufacturers' service organisations has allowed a comprehensive compilation of the typical mal-performances that occur in diesels which lead to high smoke or gaseous emissions. In general, mal-performances in the intake air system or the fuel system are the most common causes of high smoke and HC emissions, although an engine in very poor mechanical condition can have sufficient loss of lubricating oil or compression to cause high smoke and gaseous emissions.

Based on discussions with manufacturers, the data developed by EEA23 in Table 6-3 is a comprehensive listing of mal-performance in diesel engines, and their frequency of occurrence as measured in a qualitative form. In the air intake system, dusty air filters and leaky turbocharger oil seals are relatively common, while more serious turbocharger damage or problems with the intercoolers are quite rare. Valve system timing and valve leaks are also less frequently observed; if a valve leak is significant, then the cylinder can stop functioning completely due to loss of compression and the resulting vibration will make the engine undriveable in short order.

On the fuel system side, governor tampering and tampering with the "air-fuel ratio control" (also known as throttle delay) are widely acknowledged as the most common forms of tampering, although even these have been declining in recent years. Advancing the maximum fuel stop or advancing the injection timing is more rare as these are not easily accomplished, but advancing injection timing for the 1977-1984 engines (when the California engines were designed to meet NO_x standards by injection timing retard) may occur in the field.

Problems with injectors vary in severity, as most injectors are replaced only once between rebuilds, if at all. Fouling of injectors or spray hole erosion may be common in older trucks but serious injector problems will, if uncorrected for a long time, lead to serious engine damage. An incorrect injector size could be used during replacement or rebuild, but this may simply raise the maximum fuel delivered to another certified rating level (i.e., it may result in the engine producing more horsepower, but with no increase in emissions per HP produced). However, in some cases, the mismatch between the existing turbocharger/intake system and the upsized injector may be so severe that high emissions could result.

Table 6-3: Effect and Frequency of Component Mal-Performances in Heavy Duty Diesel Engines

Components	Effect on Emissions	Frequency
Air Filter (Dirty)	Can increase full throttle smoke considerably	Extent of blockage varies, but is relatively common
Turbocharger seals worn	Can leak oil and cause smoke/HC	Minor oil leaks are common in older engines
Turbocharger damage	Significant damage is catastrophic, but minor damage has little effect on emissions	Minor nicks on turbo are common
Intercooler internal leaks	Coolant induction can cause white smoke	Rare
Intercooler plugged	High heat will increase smoke and NO_x	Unknown
Valve Timing	Incorrect timing can have minor emissions effect	Rare
Valve Leaks	Loss of compression and high smoke. Engine is hard to start.	Relatively rare, self correcting due to poor startability
Governor RPM setting	Increased RPM setting can increase HC/smoke in some trucks	Common among independent trucks
Max. Fuel. Stop setting	Increased HC/smoke at full throttle	Relatively rare
Injection timing	Advance causes increased NO_x, retard increase HC-/ smoke	Relatively rare
Throttle Delay/Air-Fuel Ratio Control	Causes excessive smoke during acceleration	Common among independent trucks
Worn injector spray holes	Increase smoke/HC	Occurs in older trucks
Injector plugging	Assymetric spray can cause increase smoke/HC	Occurs in older trucks
Injector tip cracking	Excessive smoke, but is catastrophic to engine	N/A
Incorrect injector size	Effect can vary, but HC and smoke increase with increasing injector size	Could be common in replacement of injectors
Worn piston rings	High smoke from low compression/oil leak	Relatively rare, as vehicle is hard to start
Leaking valve seals	Blue smoke from oil consumption, HC increased	Unknown
Wrong part numbers	Minor effects if mismatch is not severe	Unknown, but could be a problem with aftermarket parts

Source: EEA (1993)

The use of wrong parts (i.e., incorrect size or part number) during repair or rebuild can similarly result in higher emissions in some cases, but it is believed to be relatively rare. Very worn engines with leaky valve guides, or worn piston rings, are likely to be found near the end of the engine's useful life but a certain fraction of engines on the road are always in this range of their useful life.

A qualitative estimate of the impact on air quality can be obtained by combining the frequency of occurrence and the emissions impact. This would suggest that the biggest impact on air quality would be caused by dirty air filters, worn or plugged injectors and incorrect fuel injection system setting for the governor and throttle delay.

EEA (1993) surveyed repairs to 100 trucks that failed the ARB inspection (EEA:1993). This survey provided detailed data on 81 trucks (19 had minimal repairs or contested the ARB citation), and Table 6.4 lists the distribution of repairs observed (note that many trucks had more than one type of repair).

Table 6-4: Distribution of Repairs to 100 Trucks that Failed California Air Resources Board Inspection, 1993

Repair Type	Percent of Trucks
Air Filter	43.2
Turbocharge	6.2
Air Fuel Ratio Control	35.8
Injectors	43.2
Injection Pump Settings**	22.2
Valves	22.2
Worn Engine (Rebuild)	8.6
Injection Timing	2.2
Total	**183.6**

Source: EEA (1993)

** includes repairs to governor and air-fuel ratio control

Of course, the observed distribution is also a function of the fact that ARB uses the snap acceleration test, which may preferentially fail certain types of mal-performances. Since about 25 percent of vehicles fleet wide fail the ARB test, the above number must be multiplied by 0.25 to obtain fleet wide rates.

Under contract to ARB (1988), Radian developed a model to estimate in-use emission factors, by associating each mal-performance type (e.g. disabled puff limiter) with an emissions increase/decrease for HC, NO_x and Particulate. Radian estimated these emission effects and mal-performance rates for 19 types of mal-performances to derive a composite emission factor for all in-use HDDVs grouped by certification standard. The analysis did not estimate emissions as a function of mileage, but simply as an average for each vintage class (e.g. 1984-1988). The accuracy of this model is dependent on:

- the completeness of the list of mal-performances modelled
- the estimated emission impact
- the estimated rate of occurrence of each mal-performance type.

The Radian model has a comprehensive list of mal-performances that has been developed from direct repair evidence from ARB repair studies and by consultation with engine manufacturers. The rate at which they occur is based on the ARB repair studies and is designated as rk for each mal-performance type, k. Each mal-performance type has an effect on the emissions of pollutant I, that is labelled DE_{ik}, which represents the incremental emission effect (either as a percent of baseline emissions or as an absolute number) due to the presence of mal-performance type k.

Hence the excess emissions are given by

$$DE_I = S_{rk} \times DE_{ik}.$$

The Radian model data on mal-performance types, rates of occurrence and emission increases is documented in Appendix A as a series of three spreadsheets, for light-heavy, medium-heavy and heavy-heavy-duty engines, and DE_I is reported as a percent increase in emissions from the zero-mile level. Here, the rates (rk) of mal-performance are fleet averages, and are associated with the rate at the mid-point of a vehicle's useful life. The useful life estimates are about 180,000 miles for light-heavy engines, 300,000 miles for medium-heavy engines, and 500,000 miles for heavy-heavy-duty engines. Using the VMT weights implied from registration statistics, the average mid-point of the useful life is 190,000 miles for the fleet.

The Radian model directly indicates the percentage increase in emissions at the mid-point of HDDV useful life, and it is assumed that the deterioration occurs linearly with mileage, as is common in all EPA emission inventory models. The impact of inspection and repair is modelled as a reduction in the rate of occurrence (rk) of mal-performances. This reduction is calculated from the mal-performance identification rate, which is a function of the test and standard used, and a repair rate that represents the percent of properly repaired vehicles. The Radian model's predictions of increases in emissions from initial levels, for HC, NO_x, and PM, are provided in Table 6-5.

Available limited data on these issues suggest that the Radian model is reasonable, and it has since been updated by EEA (1993) with more recent and complete data on mal-performances rates. Based on this updated version, the "average" emissions increases over the useful life by pollutant type for the California fleet in 1995 are:

- HC: - 34.0 percent
- NO_x: - 6.6 percent
- Particulate: - 43.7 percent

These above percentages indicate the fraction of total emissions associated with trucks emitting above the certification level.

Interestingly, the analysis of the 22 trucks from MY1979 described in the previous subsection leads to similar estimates of increased emissions. The analysis of the Cummins engine data provided statistically significant coefficients of deterioration for each pollutant. Estimating the deterioration at the mid-point of a HDDV's life (150,000 miles) leads to the following increases in emission estimates from the regressions shown in Table 6-1.

- HC - 36 percent (based on Cummins engines)
- NO_x - ~ 0 percent
- Particulate- 41 percent (based on all engines)
-

These data suggests that the Radian models' predictions of excess emissions are correct at least in the order of magnitude sense. Based on these data one can conclude that the in-use deterioration of HC and PM from component mal-performance is very significant.

Table 6-5a: Radian Model of Excess NO_X Emissions; Heavy-Heavy-Duty Diesel Vehicles

Defect	Frequency of Occurrence				NOx Emissions Increase of Individual Defec				NOx Model Year Group Emissions Increase				HC Emissions Increase of Individual Defec				HC Model Year Group Emissions Increase			
	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+
Timing Advanced	8	12	5	5	50	50	60	60	4.0	6.0	3.0	3.0	20	20	30	30	1.6	2.4	1.5	1.5
Timing Retarded	15	10	3	3	-20	-20	-20	-20	-3.0	-2.0	-0.6	-0.6	50	50	50	50	7.5	5.0	1.5	1.5
Minor Injector Problems	20	18	15	15	0	0	0	0	0.0	0.0	0.0	0.0	10	10	20	20	2.0	1.8	3.0	3.0
Moderate Injector Problems	12	10	8	8	-5	-5	-5	-5	-0.6	-0.5	-0.4	-0.4	150	150	300	300	18.0	15.0	24.0	24.0
Severe Injector Problems	3	3	3	3	-10	-10	-10	-10	-0.3	-0.3	-0.3	-0.3	500	500	1100	1100	15.0	15.0	33.0	33.0
Puff Limiter Misset	29	21	2	0	0	0	0	0	0.0	0.0	0.0	0.0	10	10	10	10	2.9	2.1	0.2	0.0
Puff Limiter Disabled	30	23	5	0	0	0	0	0	0.0	0.0	0.0	0.0	20	20	20	20	6.0	4.6	1.0	0.0
Maximum Fuel Stop Set High	24	18	3	3	10	10	10	10	2.4	1.8	0.3	0.3	0	0	0	0	0.0	0.0	0.0	0.0
Clogged Air Filter	18	14	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Wrong/Worn Turbo	11	8	5	5	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Intercooler Clogged	3	7	5	5	10	20	25	25	0.3	1.4	1.3	1.3	-20	-20	-20	-20	-0.6	-1.4	-1.0	-1.0
Other Air Problems	13	15	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Engine Mechanical Failure	1	1	1	1	-10	-10	-10	-10	-0.1	-0.1	-0.1	-0.1	200	200	300	500	2.0	2.0	3.0	5.0
Excess Oil Consumption	4	4	4	4	0	0	0	0	0.0	0.0	0.0	0.0	300	300	300	300	12.0	12.0	12.0	12.0
Electronics Failed	0	1	3	3	0	0	0	0	0.0	0.0	0.0	0.0	0	30	50	50	0.0	0.3	1.5	1.5
Electronics Tampered	0	6	20	20	0	30	80	80	0.0	1.8	16.0	16.0	0	0	0	0	0.0	0.0	0.0	0.0
Catalyst Removed	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	100	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	40	100	0.0	0.0	0.0	0.0
EGR Disabled	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
All Defects									2.7	8.3	19.4	19.4					70.7	61.3	81	81.4

Table 6-5b: Radian model of excess HC emissions, Heavy-heavy-duty diesel vehicles

Defect	Frequency of Occurrence				PM Emissions Increase of Individual Defec				PM Model Year Group Emissions Increase				Fuel Consumption Emissions Increase of Individual Defec				Fuel Consumption Model Year Group Emissions Increase			
	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+	1960-87	1988-90	1991-93	1994+
Timing Advanced	8	12	5	5	10	10	0	0	0.8	1.2	0.0	0.0	0	-2	-0.5	-5	0.0	-0.2	-0.3	-0.3
Timing Retarded	15	10	3	3	30	40	100	100	4.5	4.0	3.0	3.0	7	7	10	10	1.1	0.7	0.3	0.3
Minor Injector Problems	20	18	15	15	35	35	70	70	7.0	6.3	10.5	10.5	2	2	2	2	0.4	0.4	0.3	0.3
Moderate Injector Problems	12	10	8	8	200	200	400	400	24.0	20.0	32.0	32.0	5	5	5	5	0.6	0.5	0.4	0.4
Severe Injector Problems	3	3	3	3	700	700	1500	4200	21.0	21.0	45.0	126.0	10	10	10	10	0.3	0.3	0.3	0.3
Puff Limiter Misset	29	21	2	0	20	20	50	50	5.8	4.2	1.0	0.0	1	1	1	1	0.3	0.2	0.0	0.0
Puff Limiter Disabled	30	23	5	0	50	50	100	100	15.0	11.5	5.0	0.0	2	2	2	2	0.6	0.5	0.1	0.0
Maximum Fuel Stop Set High	24	18	3	3	20	20	20	20	4.8	3.6	0.6	0.6	2	2	2	2	0.5	0.4	0.1	0.1
Clogged Air Filter	18	14	8	8	40	40	50	50	7.2	5.6	4.0	4.0	2	2	2	2	0.4	0.3	0.2	0.2
Wrong/Worn Turbo	11	8	5	5	40	40	50	50	4.4	3.2	2.5	2.5	1	1	1	1	0.1	0.1	0.1	0.1
Intercooler Clogged	3	7	5	5	40	40	50	50	1.2	2.8	2.5	2.5	2	2	2	2	0.1	0.1	0.1	0.1
Other Air Problems	13	15	8	8	40	40	40	40	5.2	6.0	3.2	3.2	1	1	1	1	0.1	0.2	0.1	0.1
Engine Mechanical Failure	1	1	1	1	150	150	300	500	1.5	1.5	3.0	5.0	7	7	6	6	0.1	0.1	0.1	0.1
Excess Oil Consumption	4	4	4	4	150	150	300	600	6.0	6.0	12.0	24.0	0	0	0	0	0.0	0.0	0.0	0.0
Electronics Failed	0	1	3	3	0	30	60	60	0.0	0.3	1.8	1.8	0	3	3	3	0.0	0.0	0.1	0.1
Electronics Tampered	0	6	20	20	0	0	50	50	0.0	0.0	10.0	10.0	0	0	-5	-5	0.0	0.0	-1.0	-1.0
Catalyst Removed	0	0	0	0	0	0	40	0	0.0	0.0	0.0	0.0	0	0	-1	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	200	300	0.0	0.0	0.0	0.0	0	0	-3	-3	0.0	0.0	0.0	0.0
EGR Disabled	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
All Defects									136.6	118.2	156.7	240.6					4.5	3.4	0.8	0.6

The advent of particulate standards in 1988 and 1991, and improvements to engine technology have brought about dramatic reductions in certification HC emissions levels even though the HC emission standards are unchanged since 1984, at 1.74 g/kWh. In the early and mid-1980's, actual certification HC levels were in the 0.94 to 1.21 g/kWh range. Certification levels declined to the 0.4 to 0.67 g/kWh range in 1991, indicating a 50 percent reduction in emissions. In 1998, many engines have certification HC levels of less than 0.27 g/kWh, i.e. at levels approaching ten percent of the standard!

These reductions have not been taken into account in the EPA emission factors or into the Radian model, and both models are probably overestimating HC emissions from HDDV's by as much as a factor of 2 for 1991 and later engines.

In contrast to the U.S. models that emphasise the role of component mal-performance, European models have tended to assume that the test sample reflects the performance of the fleet as a whole. It is possible that truck owners are more law abiding in Europe relative to the U.S. and tampering may be relatively rare, especially in Germany and Switzerland. However, conversations with researchers revealed that European test vehicles are usually obtained from large fleets on a voluntary basis, so that tampered or mal-performing vehicles are unlikely to be submitted for testing.

The TUV has, however, developed a 'modal' model that is capable of forecasting emissions of any truck (engine/transmission) over an arbitrary driving cycle. One major finding of the model is that mountainous terrains (gradients) have very large effects on NO_x emissions (TUV-Rheinland:1995). A two percent gradient results in a near doubling of NO_x relative to level road, while a six percent gradient results in NO_x levels four times as high. This effect has not been studied widely in the U.S.

7 EMISSIONS CONTROL STRATEGIES

7.1 TYPES OF STRATEGIES

Strategies to control emissions from in-service vehicles have followed two distinctly different paths. The first method attempts to maintain emissions from in-service vehicles relatively close to certification and design levels. The second method attempts to reduce emissions from in-service vehicles by retrofit of new technology or upgrading of engines during rebuild. Both strategies have been attempted with varying degrees of success in the U.S. and Europe. Japan has only an annual inspection program for diesel vehicles as part of their program to maintain emissions at certification levels. Even in the U.S. and Europe, retrofit and rebuild control programs are just emerging as a potential option, and these strategies are not yet well proven in practice.

The maintenance of emissions by inspecting in-service vehicles is used widely, although many programs are using test methods that may be not be effective, or are completely ineffective at worst. Programs to retrofit technology have largely focused on public use vehicles such as buses or government owned trucks, although there are some innovative market based approaches encouraging owners retrofit technology to obtain emission credits. These strategies are discussed below.

7.2 INSPECTION/MAINTENANCE PROGRAMS

Much of the motivation for subjecting heavy-duty vehicles to inspection/maintenance programs is the public perception of diesel smoke, as well as the real threat of the carcinogeniety of smoke particulate. Virtually all of the ongoing programs to control in-service have focused on smoke emissions, and the accompanying reduction (or increase) in gaseous emissions as a result of reducing smoke has not received any attention except in isolated cases. Indeed, outside of analyses conducted by California in the early-1990s, we have not been able to find any attempt to characterise the other benefits of smoke reduction programs that are now in place in most OECD countries.

However, there are a number of inspection maintenance programs in Europe for light-duty diesel vehicles, and there have been some recent programs to develop more sophisticated tests for diesel inspections. Currently, most European diesel car and light-truck inspection programs test only for diesel smoke, and there are no broad conclusions for reductions of emissions of criteria pollutants. A 1998 study sponsored by the EU attempted to quantify the cost-benefit of light duty diesel inspections using two alternative smoke tests. All EC countries and Japan have truck inspection programs although the quality varies widely between European countries. Virtually all programs are based on smoke emissions as an indicator of pass/fail status.

Seven states in the U.S. currently have active heavy-duty I/M programs with two others operating pilot programs. Light-duty diesel vehicles are included in many state I/M programs (they are exempt in some states), but generally use the same test as for gasoline vehicles; the test is usually irrelevant to the diesel. Since there are so few light-duty diesels in the US, there has been insufficient attention to this fact.

Smoke emissions are generally measured in terms of opacity, which is simply the percentage of light blocked by the smoke plume. Opacity is measured with an opacimeter (or smoke meter), an instrument that measures the amount of light that can be transmitted though an exhaust plume (and, by extension, the amount of light scattered or absorbed by an exhaust plume). There are basically two kinds of opacimeters: Full flow, end of line opacimeters and partial flow opacimeters.

Full flow opacimeters measure the opacity of a cross section of the full exhaust plume just as the plume exits a vehicle exhaust pipe. Because exhaust pipes are not of standard size and shape, the length across which the transmitted light must pass (i.e., the path length) and therefore, the number of smoke particles available for scattering and absorption can very across test vehicles. For this reason, all opacity readings from full flow opacimeters must be corrected to a standard path length to avoid testing inconsistencies. Partial flow opacimeters take a sample of the exhaust gas from inside the exhaust pipe and measure opacity within a cell of fixed path length. Thus, all readings taken with a given partial flow opacimeter are consistent (and independent of the exhaust stack diameter), but generally are still corrected to a standard stack diameter for consistency with full flow smoke meter readings.

A typical I/M program consists of standardised test and measurement procedures, a set of pass/fail cut points, and an enforcement mechanism. Smoke tests can be loosely classified into two types: transient and steady state. Transient tests measure smoke over a changing engine speed and load cycle, while steady-state tests measure smoke during a constant speed and load condition. Each can be effective in detecting certain typical engine mal-performances although transient tests are generally more robust in terms of the scope of mal-performances identified.

There are two common transient tests:

- The On-Road Acceleration Test, where the vehicle is either started from a standstill or is rolling at low speed, following which the accelerator is depressed to the maximum (or wide-open throttle) position and held there for six to tem seconds or more.
- The Snap Acceleration (or Snap Idle) Test, which requires, with the transmission in neutral and the engine at normal idle, the accelerator pedal be depressed to the maximum, or wide-open throttle, position. The pedal is held at this position for five seconds or until the engine reaches governed speed. The pedal is then released and the engine allowed to return to normal idle.

There are four common steady-state tests currently in use:

- The Stall Test, where the vehicle engine is operated at wide-open throttle, with the automatic transmission engaged in drive, and the brakes engaged to prevent vehicle motion.
- The Lug-Down Test, where the engine is operated at wide-open throttle with the vehicle mounted on a dynamometer. Dynamometer load is increased to reduce engine speed (i.e., “lug-down”) from rated RPM to some fraction (generally around 70 percent) of rated RPM. In the absence of a dynamometer, the vehicle can be “lugged” down by the careful application of the vehicle brakes
- The Idle Test where the vehicle’s exhaust smoke opacity is measured at normal curb idle or high idle.
- The Cruise Mode (i.e., Clayton Key Mode) Test, where the vehicle is tested by applying a single load, while being operated at a constant speed.

The most common test procedure currently applied in the U.S. to heavy-diesels is the SAE J166725 snap acceleration test procedure, recently promulgated by the Society of Automotive Engineers. This test procedure was jointly developed by the regulatory and trucking communities and specifically addresses industry concerns with its predecessor J1243 test procedures.

The SAE J1667 test incorporates:

- a specific method of performing the snap-acceleration test;
- correction factors for normalising measured smoke opacity when measurements are made at alternative optical path lengths and non-standard ambient conditions;
- specifications for the smoke meter, and especially for overall instrument response time.

In general, transient testing provides an effective means of identifying the short duration smoke events that characterise a variety of common mal-performances. On the other hand, steady-state tests at wide-open throttle (i.e., lug down) do not identify several common mal-performances, but identify some mal-performances that the transient tests do not. These mal-performances are not as common, but can have a significant emissions impact. The idle and cruise mode tests are largely ineffective in detecting most mal-performances, since they are conducted at part throttle.

A summary of state specific U.S. Test programs is as follows:

State	Test	Failure Rate
Arizona	Lug-Down	4.50%
California	SAE J1667	Roadside Test of Potential Failures Only
Colorado	Lug Down	< 1%
Nevada	SAE J1667	Roadside Test of Potential Failures Only
New Jersey	Rolling Acceleration or Stall-Test	Not Available
Washington	SAE J1667	2 to 3 percent

Source: EEA (1999)

The failure rate is a function of both the test used and the pass/fail standards. In most states in the U.S., J1667 test standards are usually 40 percent opacity for 1991 and later vehicles, and 55 percent opacity for 1990 and older vehicles, but is up to 70 percent opacity in some states. The standard for 1990 and older vehicles of 55 percent opacity appears to fail a significant portion of mal-performing vehicles. On the other hand, the 40 percent standard appears to be almost completely ineffective with modern engines, especially those with electronic controls. Electronic controls can easily disable fuel systems if the vehicle is not in gear, making the J1667 procedure useless. Failure rates for modern (post-1994) U.S. engines are extremely low, typically less than three percent.

Most EC countries also use the snap acceleration test (sometimes call free acceleration test) though some regional jurisdictions in Germany require both the snap acceleration test and the lug-down test. The European snap acceleration test is not identical to the J1667 in terms of meter response time and technical criteria to determine a valid test, and these specifications also very from country-to-country. For example, Germany has a time specification for the RPM increase on the free acceleration test, while France does not.26

The largest difference between the U.S. and Europe is that the smoke opacity standards in many the EC countries are type specific and vary from engine model to engine model. The standards are actually suggested by the engine manufacturer, leading to considerable complexity in administration. Moreover, the engine manufacturers have an incentive to make the standards relatively lax, so that so engines with marginal mal-performances are not failed.

Most European countries also use the free-acceleration test for light-duty vehicles, with opacity standards that are either model specific or equivalent to about 40 to 50 percent opacity (peak). In a recent (1998) study by the European Commission, a number of inspection type short tests were investigated by European Research laboratories. The first type of test involved a dynamometer based short transient cycle over which only smoke emissions were monitored. The second was the free acceleration test. Although the report concluded that the first type of test showed promise, it is not well supported by the data. Indeed, the correlation between smoke measurements over the short test and PM emissions on the certification type test was very dependent on one data point for a gross PM emitter. Removal of this one data point resulted in the correlations becoming substantially worse, to the point where the benefit over the free acceleration test was not large. At this point in time, it can be stated that there is no good test for inspection of diesel light duty vehicles, but it should be noted that the free-acceleration test can spot gross emitters of PM (of course, such vehicles can be spotted by the unaided eye easily)

In Japan, the free acceleration test is also used, but the smoke measurement is based on a long averaging time instrument so the results are not comparable to the SAE J1667 test. However, Japan implements a standard of 40 percent opacity for pre-1999 trucks, and 25 percent opacity for 1999 and later vehicles.

While detailed failure rates for EC countries and Japan are not available, several leading researchers confirmed to EEA that only about one percent of both light-duty and heavy-duty vehicles tested actually fail the test. Hence, the primary value of the test appears to be as a deterrent to tampering in Europe and Japan.

Failure rates are somewhat greater in the U.S., but still quite low given the number of smoky trucks observed usually on the road. Only the California Roadside Program has addressed the issue of targeting likely failures for the test, and is hence more effective. Since high smoke emitters can be visually identified, targeting of potential failures is quite easy.

As noted, only California has attempted to estimate the benefits of the heavy-duty vehicle smoke opacity reduction program. Many researchers have claimed that the free acceleration test based smoke opacity has no correlation with HC or PM emissions measured on the 13-mode or transient test. While this is an accurate statement, high smoke on the free acceleration test (at lest for older mechanically controlled engines) is indicative of a defect in the air-fuel ratio control system. Depending on the defect, this can have a large or small effect on emissions measured on a certification type test. Hence, the free acceleration test is a mal-performance indicator rather than an emissions indicator.

The mal-performance model described in Section 6 provides an appropriate tool to estimate the benefits of an I/M program. Analysis for California shows that the I/M program is capable of identifying at least half of all "excess" emissions of HC and PM on older mechanically controlled engines. No recent analysis has been done on the benefits for newer electronically controlled engines, but the absolute quantity of excess emissions as well as the percent identified have undoubtedly declined relative to older engines. The high level of excess emission may be a phenomenon that is U.S. specific, since the rates of tampering and mal-maintenance are potentially much higher in the U.S., relative to European levels.

As noted, virtually no analysis of inspection program cost-effectiveness has been performed outside of the U.S., with most existing analysis from California of their roadside smoke inspection program. In a recent study for Denver (Colorado), data from the California program and the existing Colorado program (which uses a lug down test) was utilised to estimate the cost-effectiveness of different types of programs: centralised annual inspection vs. random roadside, SAEJ1667 test vs. lug down.

Based on actual administrative and test costs, and estimated repair costs and emission reductions, the analysis developed the cost-effectiveness in terms of U.S. dollars per ton of (HC + PM + NO_x) reduced. They are as follows:

- Centralised Program, Lug Down test - $3260 / ton
- Centralised Program, J1667 test - $3030 / ton
- Centralised Program, J1667 + lug down test - $3430 / ton
- Roadside Program, J1667 test - $2430 / ton

One of the major findings is that program type has a major impact on costs. In centralised programs, all vehicles are inspected and only ten percent or so may fail. The large cost of inspecting the other 90 percent makes such programs significantly more expensive than roadside programs that target likely failures by visually identifying potential failures. The similarity of all of the cost per ton figures is driven partly by the deterrent effect of having any program, which reduces tampering.

The 1998 EC report referred to earlier also attempted to calculate the cost effectiveness of diesel light-duty vehicle inspection using the (admittedly) low quality tests. Repair costs for vehicles failing the tests appear to have been assumed, and also appear quite low, at Euro 200 to 300. In spite of this relatively low cost assumed, the cost effectiveness per ton of PM reduction was calculated at Euro 34,000. This cost is an order of magnitude higher than the cost-effectiveness of heavy-duty vehicle inspection calculated in Denver. Although the methodologies are not the same, the costs provide at least an order of magnitude sense but may also be influenced by the relatively low rates of mal-performance in Northern Europe.

It is not clear if Australian cost effectiveness figures will be similar since the benefits are quite dependent on mal-performance rates in the fleet. If the mal-performance rates are quite low (as is potentially the case in Europe), the costs per ton will be much higher.

7.3 RETROFIT AND REBUILD RELATED PROGRAMS

The potential to decrease emissions of in-service diesels through retrofit of new technologies to older vehicles or by rebuilding engines to new standards has received considerable attention in Europe and the U.S. over the last five to seven years.

7.3.1 *European Developments*

To date, there are no regulations in Europe requiring the retrofit of technologies or the rebuilding of engines to more stringent emissions standards, for either light- or heavy-duty vehicles. The EC regulation only requires that rebuilt engines meet the original specification that the engine was designed to; the same regulation applies to re-engined vehicles. However, in the case of re-engined vehicles, we understand that most operators in Europe simply buy a current model engine of the same make, so that an upgrade occurs ‘defacto’ simply due to convenience.

While there are no requirements that legally enforce retrofit or upgrade, there are many organisations in Europe that are voluntarily retrofitting engines with newer technology, mostly trap oxidisers or oxidation catalysts. The vast majority of these voluntary retrofits have been by the Metropolitan Transport Organisations (state-owned) for the bus fleet. Both Germany and the U.K. confirmed that these are probably several hundred buses in each country that have been retrofitted with trap oxidisers. A few large transport companies have retrofitted a handful of trucks (the total in the EC is a few hundred) as a public relations measure or as a demonstration program. Virtually all of the retrofit has been with trap oxidisers that primarily affect PM emissions, and to a lesser extent, HC emissions. There have been some retrofit of oxidation catalysts to light-duty vehicles in Sweden and Germany, but these have largely been as demonstration programs in Europe.

The retrofit devices for heavy-duty vehicles are commercially offered by catalyst manufacturers such as Engelhard and Johnson-Matthey. Each country is certifying retrofit devices to meet a minimum performance requirement that requires a reduction in PM of at least 20 to 25 percent and HC by a similar amount, without increasing NO_x emissions or noise. Newer regulations in Germany now require a minimum performance of 70 percent reduction in PM from Euro I or earlier certification engines, and a number of devices are new available commercially. The certification is by a publicly owned laboratory; as an example, TUV-Essen is responsible for certifying such devices for Germany.

Virtually no assessment of programs that aim at reducing NO_x emissions from in-service vehicles has occurred in Europe. NO_x can be reduced from in-service engines by a number of actions ranging from injection pump and injection timing recalibration to the addition of an air-to-air intercooler in non-intercooled or jacket water intercooled engines. We are unaware of any European program that has focused on these aspects, although there is a white paper to be released shortly in England that may discuss such issues.

The principal reason for the lack of any major activity in retrofitting new technology is the very high cost of retrofit. Typical costs for a trap oxidiser or oxidation catalyst are around U.S. $1000 per litre of engine displacement. Hence, retrofitting a typical heavy-duty truck powered by an 11-litre engine with a trap oxidiser could cost U.S. $11,000 (over A$16,000) or more, which is prohibitive for a commercial truck owner. Light-duty vehicle retrofit costs are also on the same order, and a typical small car engine must be retrofitted with a catalyst that can easily exceed US$1000, or A$ 1500. Costs are coming down with increased sales and learning, but the cost decline in quite slow.

Sweden is using a novel method to encourage the retrofit or upgrade of heavy-duty engines. It has created environmental zones in its three largest cities: Stockholm, Goteburg and Malmo. The zone essentially covers the entire central business district of the cities. Within these zones, municipal councils have the right to restrict heavy-duty diesel vehicles that do not meet stringent emission standards. The current regulation (due to be revised next year) prohibits diesel heavy-duty vehicles that do not meet the Euro II requirements from these areas, but provides general dispensations to two categories of vehicles:

- vehicles less than eight years old;
- vehicles retrofitted with exhaust devices that meet specific emissions reduction criteria.

Two levels of performance have been set up for retrofit technologies. Level A requirement a PM reduction of 25 percent and an HC reduction of 60 percent relative to untreated exhaust. Level B requires a PM reduction of 80 percent and an HC reduction of 60 percent. Vehicles less than ten years old must be fitted with devices meeting the Level A requirements, while vehicles older than ten years must utilise devices certified to Level B.

Conversations with environmental authorities of Stockholm and Goteberg confirmed that many older buses are now fitted with Level A devices and a few with Level B devices. There has been a redirection of newer trucks to the environmental zones, but authorities believe that several hundred private trucks have adopted Level A and Level B rated retrofit devices in all of Sweden. Hence, it is regarded as a relatively successful local air pollution control strategy.

While other countries in Europe have restricted traffic zones for older vehicles, these regulations are not directed especially at retrofit devices.

7.3.2 *U.S. Developments*

The U.S. has moved ahead on some specific retrofit and rebuild requirements for heavy-duty vehicles only, that are now part of the regulations. There are four major actions that now affect retrofit and rebuild in the U.S.:

- retrofit and rebuild requirements for 1993 and earlier urban bus engines;
- the California Low Emission Vehicle Emissions Credit Program;
- the North-Eastern States Voluntary Heavy-Duty Retrofit Program;
- the Low NO_x Emissions Rebuild Program.

Of these, the first and last program are driven by regulatory requirements, while the California and North-Eastern State Program are market driven approaches. Separately, there are special financial incentives available for conversion to alternative fuels, but those are not considered here.

The Clean Air Act (as amended in 1990) required EPA to promulgate regulations affecting the replacement or rebuilding of 1993 and earlier model year urban buses. Engines replaced or rebuilt after January 1, 1995, are required to comply with an emission standard or control technology reflecting the best retrofit technology and maintenance practices achievable. The act restricts this requirement to 1993 and earlier model year urban buses operating in Metropolitan Statistical Areas and Consolidated Metropolitan Statistical Areas with 1980 populations of 750,000 or more.

In early 1993, EPA published final Retrofit/Rebuild Regulations for 1993 and Earlier Model Year Urban Buses. The regulations require affected urban bus operators to comply with one of two program options, beginning January 1, 1995. Option 1 established particulate matter (PM) emission requirements for each urban bus in an operator’s fleet when the engine is rebuilt or replaced. Option 2 is a fleet averaging program that sets out specific annual target levels for average PM emissions from urban buses in an operator’s fleet. The two compliance options are designed to yield equivalent emissions reductions for approximately the same cost.

Option 1 requires affected urban buses to meet a 0.10 g/bhp-hr (0.13 g/kWh) PM standard at the time of engine rebuild or replacement. This option is effective only if equipment had been certified by EPA for at least six months as meeting the 0.10 g/bhp-hr standard for less than a life cycle cost limits of $7,940 (in 1992 U.S. dollars). The regulation allows transit operators to plan their budgeting and procurement activities, and to help ensure an adequate supply of parts are available from equipment manufacturers. If certified equipment is available, then affected buses must use equipment which reduce PM emissions by 25 percent, if such equipment has been certified by EPA for less than a life cycle cost limit of $2,000 (in 1992 U.S. dollars).

Option 2 is an averaging-based program that requires bus operators to meet an annual average fleet PM level, instead of requiring each individual rebuilt engine to meet a specific PM level. On an annual basis, an operator must reduce its “actual” PM emissions from its buses to a level no greater than its annual target level for the fleet (TLF). The operator calculates the TLF for each year of the program, beginning calendar year 1996, based on actual fleet composition, an assumed engine rebuild and retirement schedule, and EPA’s determination of expected PM levels for each engine model. As each engine in a fleet is assumed to be rebuilt in a particular calendar year, the TLF calculations "switch" from a "pre-rebuild" PM emission level to a lower "post-rebuild" level that reflects the assumed use of lower-emitting, certified equipment. Over the years of the program, as the engines in a fleet are assumed to be rebuilt, this "switching" results in numerically lower TLF values.

Certification activity under the retrofit program has lagged substantially behind the schedule anticipated by EPA when the final rule was promulgated. No equipment was certified when EPA revised the post-rebuild levels based on equipment. The first certification for the program occurred on May 31, 1995, almost a year after the post-rebuild levels were revised the first time. Several rebuild/retrofit kits were certified by 1996, but none were certified to the 0.10 g/bhp-hr PM standard. EPA's assumption that certification activity would begin early was incorrect and more importantly, EPA's assumption that certification activity would be complete by mid-1996 was incorrect. For example, EPA only recently certified equipment manufactured by Engelhard Corporation that triggers the 0.10 g/bhp-hr standard for 1979 though 1989 model year Detroit Diesel Corporation (DDC) 6V92TA MUI engines. Additionally, Johnson Matthey Incorporated has been certified to supply equipment to the same standard, and applicable to these, and other, DDC engines. There are other plans for certifying equipment to the 0.10 g/bhp-hr standard for a large segment of the bus engine population.

The California and North Eastern States programs are similar in that they involve the use of emission credits that can be generated by retrofitting a heavy-duty diesel engine. In the U.S., most major metropolitan areas are not yet in compliance with the air quality requirements for ozone and are designated as non-attainment areas. In these areas, businesses that generate more emissions than some allowable level are required to offset the increase by purchasing credits or helping reduce emission elsewhere, making emission reductions a marketable commodity. Hence, there is value to a private firm reducing emission by retrofit, and selling these credits can (in theory) offset the cost of retrofit either partially or entirely.

The California and North-Eastern States programs certify specific control technologies and have developed specifications on how the credits are to be calculated. In the case of diesel engines, low emission retrofits can be specific to a range of "credit" standards that are at least 30 percent lower than the "ceiling" standard. The ceiling standard is the original certification standard. The administration of these credit programs is at the local air quality control authority. To date, however, the number of voluntary retrofits has been very small (a few hundred vehicles nationally) largely because the cost of retrofit is very much higher than the market value of the credits.

The newest program is one that has come about from a settlement of a regulatory action by EPA against the diesel engine manufacturers. As referred to in Section 7, the EPA believed that modern diesel engines employed "cycle beating" techniques to met current emission standards, and initiated legal actions against engine manufacturers. As part of the settlement, the manufacturers have agreed to develop low NO_x rebuild kits for a range of popular engine models manufactured between 1993 and 1998. These kits will essentially bring the NO_x levels of affected engines down by about 25 percent. The kit is to be available at no extra cost to rebuilders and owners, and all engines within the model year range that are selected by manufacturers must be rebuilt using this kit. Such kits are expected to be available in the marketplace shortly.

As noted, only the two regulatory programs are expected to have a significant influence on rebuild and retrofit. The U.S. EPA is considering other rebuild and retrofit requirements for heavy-duty diesels but no actions are expected in the near future.

No good estimates on cost-effectiveness of either a retrofit or rebuilt or rebuild program is available. However, the cost of retrofit ranges from A$15,00 to A$20,000 for a typical diesel truck with engines ranging from six to ten litres displacement. Over the typically lifetime of the retrofit device of 400,000 to 500,000 km, computed reductions in particulate emissions (for a typical 15 ton rigid truck) is on the order of 0.5 ton. Hence the cost-effectiveness in terms of dollars per ton is not very good at $30,000 to $40,000 per ton, without even including administrative cost and device maintenance cost. On the other hand, rebuild upgrade kits cold be very cost effective, but no cost data on such kits are available yet. It is widely expected that a rebuild kit could reduce NO_x by 20 to 30 percent but have an incremental cost of A$1000 or less.

8 POTENTIAL CONTROL PROGRAMS FOR AUSTRALIA

8.1 CONTEXT

Strategies to control diesel emissions in Australia must be developed in the context of the diesel fleet in Australia. A large fraction of the Australian fleet is imported from Europe and Japan, with European makes mostly in the 12 to 25 ton gross weight categories and Japanese trucks dominating the 3.5 to 12 ton category. Makes imported from the U.S. are typically in the largest trucks, those over 25 tons gross weight. Our contacts with Australian staff of major importers of diesel engines suggested that most engines imported from Europe potentially meet the Euro I standard since 1999/1994. As noted the ‘Euro O’ standards was not very stringent and most European engines sold in Australia prior to 1993 probably met ‘Euro 0’ standards. In addition, Japanese standards (relative to the Japanese test requirements on the six-mode) for lighter truck engines were not very stringent, so that on average, most Direct Injection diesels met the Euro O or even Euro I standards. Some of the trucks around five tons GVM employ IDI diesels, which have very low NO_x emissions (capable of meeting Euro III levels). Hence, strategies need to be sensitive to the Australian fleet composition.

Buses are a special case, and a majority of buses in Australia use engines from Germany or Sweden. Hence, this segment offers the possibility of harmonising control strategies with Germany or Sweden.

The Australian light-duty diesel fleet consists primarily of smaller versions of heavy-duty diesel engines, or large displacement special purpose light-duty diesel engines, most of which are sourced from Japan. While the former type of diesel has much in common with heavy-duty engines used in trucks in the 3.5 to 6 ton GVM range, the latter category is somewhat unique and there is no good understanding of their emission characteristics and control strategies for their emissions. Passenger car type diesels imported from Western Europe or Japan (of 1.5 to 2.5 litres displacement) are a relatively small contributor to total diesel emissions due to their small population, and the relevance of Western Europe’s light-duty diesel emission control programs to Australia is limited.

8.2 DETERIORATION OF EMISSIONS UNDER IN-SERVICE CONDITIONS

Although there are only a limited number of studies on the topic of in-service deterioration of emissions, there are a number of findings of potential interest to Australia.

Since the Euro 0 and Japanese standards to 1998 were not very stringent, the potential of older in-service engines exceeding these standards is quite small. Most engines will have emissions well below applicable standards, and only severe tampering or mal-maintenance will cause engines to exceed the standards appreciably. This finding is likely to affect a significant portion of the Australian fleet.

The findings from Europe indicate that about five to ten percent of the heavy-duty fleet will likely exceed the Euro I and Euro II standards (plus a margin of safety of ten percent of the standard). This represents a fleet wide average failure rate, and actual failure rates will likely increase with truck age or use. In contrast, a much larger portion of the engines (20 to 25 percent) certified to standards in the U.S. prior to 1991 (approximately equivalent to Euro I or Euro II) are likely to be exceeding standards in the U.S. There is a widespread belief (unproven to date) that tampering and mal-maintenance rates are higher in the U.S. than in Europe. It is not clear from available data where Australia is in terms of mal-performance rates.

Since emission tests of heavy-duty trucks are expensive, only a limited sample of in-use trucks can be tested. However, the engineering model developed for California may be a useful tool to combine survey-based data on mal-performance rates in Australia with available emissions data to develop in-use emission factors. This method has been used with some success in the U.S. The survey of mal-performance rates in the in-service Australian truck fleet needs to be established in order to develop an appropriate control strategy for in-use emissions as well.

The European experience with light-duty diesels is similar, in that few vehicles exceed standards. Even the Euro I and II standards applicable to this category of vehicles are not very stringent relative to near uncontrolled rates, so that few vehicles fail gaseous emission standards. Failure of PM standards is more common, but gross emitters (emitting over 5 times the standard) may be relatively rare. It is also not clear wether data from old mechanically controlled IDI diesels will be representative of the new breed of turbocharged, electronically controlled DI diesels that will dominate the market in the future.

8.3 MAINTENANCE OF IN-SERVICE EMISSIONS

Virtually all of the programs around the world for inspection of in-service light and heavy-duty vehicle emissions have focused on smoke, and by extension, PM emissions. The snap acceleration test also appears to be the test of choice for most inspection programs, although test cycle details and the specifications of the smoke meter vary between countries. The recently published SAE J1667 procedure provides a high degree of standardisation of test details and is a possible option for Australia if it is decided that the snap acceleration test is useful under Australian conditions.

The snap acceleration test should not be thought of as a predictor of PM emissions for any vehicle, but rather as a diagnostic test to identify mal-performances present in the engine that could lead to high emissions. The actual types of mal-performances identified by the test and the relative excess emissions reduction that occurs from repair of these defects depends both on the smoke opacity pass/fail standard and the type of engine. The test works reasonably well in identifying defects on older engine models with mechanically controlled fuel systems, but does not work well with more recent electronically controlled engines. Anecdotal evidence suggests the bulk of the heavy-duty engines currently operating in Australia is of the mechanically controlled type, although the electronically controlled engines will eventually become dominant. Hence, there is a time window where the snap acceleration test could be useful to Australia. Second, and more importantly, the snap acceleration test is particularly useful in identifying defects that arise from tampering to increase power by overfuelling the engine. These types of tampering are not uncommon on mechanically controlled engines in the U.S., but this is not the case in Europe. Hence, the applicability and usefulness of the test in Australia depends to some degree on the types and rates of mal-performances present in the in-use fleet. Finally, it should be noted that the programs in the U.S. using this test have set relatively lax pass/ fail cut points so that its primary use has been has been as a method to identify “gross” emitters. The U.S. standards have also been influenced by the threat of lawsuits in the case of false failures.

Smoke measurement on the “lug down” test is also sometimes used as an adjunct or as an alternative to the snap acceleration test. Available data suggests that the lug down test does identify different mal-performances than the snap acceleration test, but the test is more difficult to conduct and is preferably performed on a dynamometer, which is expensive. The marginal benefit of this test as an adjunct to the snap acceleration test is dependent on the rate of mal-performance in the fleet of those mal-performances recognised by the lug down test.

All tests focusing on smoke emissions identification and reduction also provide reductions in PM emissions and in gaseous HC emissions but the actual reductions provided are a function of both the test employed and the rates and types of mal-performances in the fleet. It is difficult to provide a general estimate of benefits in Australia as there are no data to support any of the modelling conducted in the US. However, smoky trucks are regarded as a public nuisance and control programs can be justified on the basis of smoke reductions alone. Moreover, such programs have a deterrent effect on tampering, which can be of significant benefit to emissions. At this time, there are no developed procedures to identify high NO_x emitters, and much of the development of chassis based procedures described in Sections 3 and 4 of this report is to support the development of a short test that would allow direct measurement of all gaseous pollutants.

Manufacturers of engines have suggested direct interface with on-board diagnostics for electronically controlled engines as one method to identify emission control system defects. There have also been suggestions to inspect emission critical components by a performance check. At present, these methods are difficult to incorporate into any common inspection program due to the lack of standardised on-board diagnostics, or due to the time required to conduct performance checks of emission critical components. However, the on-board diagnostic interface may become possible in the future as the systems are harmonised around the world.

8.4 RETROFIT AND REBUILD CONTROL PROGRAMS

Retrofit programs around the world have, to date, focused on the retrofit of trap oxidisers or oxidation catalysts for the control of PM emissions and HC emissions from heavy-duty diesel engines. Programs for light–duty diesel vehicles are limited to a handful of voluntary catalyst retrofit programs. Other than the urban bus program in the US, all other approaches are voluntary or market based. The programs have been largely restricted to the urban bus market in most countries because costs of these devices are currently in the range of US $10,000 to 15,000 for a typical heavy-duty installation for the parts alone (labour costs to install the system will vary by body type). Many newer systems are capable of reducing PM emissions by 70 percent or more from a Euro I or earlier certification engine, which typically emits PM at a rate of 0.5 g/kWh. Hence, a reduction of 0.35 g/kWh is possible. For a typical urban bus, the conversion factor from g/kWh to g/km is about 2, implying a reduction of PM emissions of 0.7 g/km. Over the life of the trap oxidiser or catalyst (estimated at around 600,000 km), the lifetime emissions are reduced by 0.42 tonnes, implying an undiscounted cost effectiveness of A$38,000 per tonne (the costs could be higher).

These current cost numbers indicate why policies using market measures have had only limited appeal to date. Although the costs could decline significantly in the future, the current costs make the retrofit option a very expensive form of emission control. The main advantage with these systems is that they are 1) commercially available 2) are performance certified by an unbiased organisation and 3) have after sales support in the marketplace. Australia has the advantage that its buses use engines from Germany and Sweden, which have active retrofit device approval and performance certification programs. By accepting these certifications, Australia could adopt retrofit requirements for buses with very low administrative burdens.

No retrofit devices to reduce NO_x emissions are commercially available, although there are prototypes of reduction catalysts that are being demonstrated now. One example is the urea based SCR catalyst being developed by Siemens that can reduce NO_x emissions by 70 percent. However, these systems are still a few years from commercialisation and may also require infrastructure changes such as the need to provide urea at filling stations. System costs are very uncertain at this time, but could be in the same range as trap oxidisers. Since NO_x emissions are ten times higher in mass than PM emissions, cost per ton will be about one-tenth those cited above for PM, making these devices more cost effective.

Rebuild requirements in most EC countries have focused on maintaining the certification levels of emissions for the original engine. Rebuild requirements to reduce emissions from original levels have, to date, been implemented only in the US and one focuses on urban bus PM emissions, while the second focuses on low-NO_x rebuild kits. The bus requirements force either the re-engining of buses at rebuild with a current model engine or the retrofit of a trap oxidiser or catalysts covered in the discussion above. The low-NO_x rebuild kit is of great interest as the kit costs will be low and it could provide a 20 to 25 percent reduction in NO_x with relatively small effects on fuel consumption. The main disadvantage to Australia is that such kits will be available for only a relatively small portion of the fleet that consists of engines imported from the US between 1993 and 1998.

In the absence of manufacturer-developed kits for a low emissions rebuild, it may be possible to rebuild engines to a more recent specification. Most manufacturers often use the same basic engine block for decades and upgrade the heads, pistons and fuel injection system that can then be utilised by older versions of the engine. In some instances, the exhaust and intake pipes are relocated to accommodate an intercooler so that the upgrade may not be possible due to layout restrictions. However, the introduction of very stringent emission standards for heavy-duty diesels in recent years has resulted in manufacturers introducing many new engine models with new blocks and phasing out production of older models. As a result, this approach can only be implemented on a case-by-case basis in Australia.

One possible option for Australia is to work with the EC and Japan to encourage manufacturers to develop low emission rebuild kits for high sales volume engines. Without manufacturer intervention and assistance, it will be difficult for Australia to develop a rebuild requirement that calls for any reduction in emissions relative to the original specification. Another disincentive for Australia is that the original specification is itself unknown in terms of emissions for many pre-1996 engines, and a standard rebuild requirement for all engines will certainly involve substantial equity concerns. While reductions from certification or original levels are possible through upgrade at rebuild, research is required for identifying candidate models that are relatively common in the Australian fleet, and for identifying the type and cost of the upgrade possible.

It is possible that upgrades at rebuild can provide NO_x reductions of 2 to 3 g/kWh for pre-1996 engine that translates to 4 to 6 g/km emission reduction. Over a truck engine lifetime after rebuild of 500,000 km, a total NO_x reduction of two to three tons is possible. Costs for such kits (as an increment of the standard rebuild kit) are expected to be very low, certainly under A$1000 and possibly less than half that amount. Hence the cost-effectiveness is very good at less than $500/ton.

Table 8-1 summarises the various options for Australia. Since actual mal-performance rates in Australia are unknown, a study or survey to determine these rates would be most useful.

At present, we can comment only on the portion of the light vehicle fleet in Australia, with engines similar to the light end of the heavy-duty fleet. For these vehicles, we anticipate that the options are quite similar to those for heavy-duty vehicles. Vehicles equipped with light-duty diesel engines can have similar options, but European studies suggest that costs of emission reduction per ton are much higher. In addition, there appears to be no good method to test light-duty diesels in an inspection type situation, although development work is continuing on this topic in Europe.

Table 8-1: Summary of Heavy-Duty Vehicle Options

Program	Cost-Effectiveness*	Comments
Centralised Annual Smoke Inspection	Over $5000/ton	Deterrence is primary benefit, but inspection cost is high.
Random Roadside Smoke Inspection	Under $4000/ton	Cheaper than centralised program and more effective.
PM Trap/Catalyst Retrofit	Over $30,000/ton	Very high costs of device, but may be suitable for buses.
Upgrade at Rebuild	Potentially low, less than $500/ton	Kits need to be developed and will not be available for all trucks.

* Assumes that malperformance rates in Australia are similar to those in the U.S.

BIBLIOGRAPHY

1. U.S. 40 Code of Federal Regulations (CFR) Part 86, Appendix I, Section (f).
2. U.S. EPA (1999), Notice of Proposed Rulemaking, Control of Emissions of Air Pollution from Highway Heavy-Duty Engines, August.
3. ARB (1996), , Mobil Source Emissions Reduction Credits, California Air Resource Board Report, February.
4. Diesel net, Diesel Emissions Online, Emission Standards (site: www.dieselnet.com / standards.html).
5. SAE (1973), Diesel Engine Emissions Measurement Procedure – SAE J1003, SAE Recommended Practice, approved March 1973.
6. Hoppie, J.A. (1997), “Defining Drivetrain Losses in Developing a Cycle for Engine and Chassis Dynamometer Test Compliance,” Masters These, West Virginia University.
7. TUV-Rheinland (1995), Exhaust Emission Factors for Heavy-Duty Vehicles in the Federal Republic of Germany for Reference Year; 1990, Final report, UFO Pan No. 104 05 151 / 02, March.
8. Van Gompel, P. and Verbech, R. (1993), “Eindrapport Diesel-Controle Methode”, TNO Report 93.OR.VM.023.1 / PVG / RV, Netherlands.
9. SAE (1982), Fuel Economy Measurement Test for Trucks and Buses – SAE J1376, SAE Recommended Practice, approved July 1982.
10. Clark, N.N., et al (1998), Development of a Heavy-Duty Chassis Dynamometer Driving Route: Phase I report; prepared for the Midwest Research Institute and National Energy Research Laboratory, West Virginia University, May 27.
11. France, C.J. and Wysor, T. (1978), Selection of Transient Cycles for Heavy-Duty Vehicles, Report HDV-78-02, U.S. EPA, June.
12. France, C.J. (1978), Transient Cycle Arrangement for Heavy-Duty Engine and Chassis Emissions Testing, Report HDV-78-04, U.S. EPA, August.
13. Harris, D.B, King, F.G., Brown, J.E. (1995), Development of On-Road Emission Factors for Heavy-Duty Diesel Vehicles Using a Continuous Sampling System, presented to the AWMA Conference on Emissions Inventory, Research Triangle Park, October.
14. Harris, D.B, King, F.G., Brown, J.E. (1998), Heavy-Duty Truck Test Cycles: Driveability versus Realistic Engine Exercises, draft EPA report.
15. EEA (1985), Mobile Source Emissions Analysis for California, Report to the California Air Resources Board, June.
16. Cornetti, G.M., et. Al. (1988), U.S. Transient Cycle versus ECE R.49 13-Mode Cycle, SAE Paper 880715, March.
17. Rijkeboer, R.C., et al. (1998), Final Report In-Use Compliance Program: Trucks 1996-1997, TNO Report No. 99.OR.VM.040.1 / RR, November.

18. McCormick, R.L., et. Al. (1998), Comparison of Chassis Dynamometer In-Use Emissions with Engine Dynamometer FTP Emissions for Three Heavy-Duty Diesel Vehicles, SAE Paper 982653, October.

19. ARB (1998), Demonstration of a Heavy-Duty Vehicle Chassis Screening Test for Compliance Testing Heavy-Duty Engine, Final Report, California Air Resources Board Contract No. 94-347, July 1998.

20. MTC (1995), Emission for Four Heavy-Duty Vehicles, Motor Test Centre Report No. MTC 9406A, October 1995 (Sweden).

21. EEA (1993), Feasibility Study for an I/M Program for Heavy-Duty Vehicles, Report to the California Bureau of Automotive Repair, January.

22. ARB (1988), Heavy-Duty Vehicle I/M Study, California Air Resources Board Contractor report from Radian, May 1988.

23. EEA (1999), personal communication between Mr. D. Hassel of TUV-Rheinland and Mr. K.G. Duleep. Table 2-2 .