Automotive emissions from a Nordic perspective

LITERATURE REVIEW

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A REPORT FOR

THE SWEDISH ROAD ADMINISTRATION

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SUMMARY

The present report is a non-exhaustive review on automotive emissions regulations, technology and alternative fuels with special focus on Nordic conditions. The aim is to describe the current status and the possible near future as Euro 5 has recently gone into force and the work with Euro 6 is being finalized.

The Swedish passenger car fleet is briefly described in the introducing section followed by a discussion on how low temperature affect car operation and emissions. Next a section is dedicated to emission reduction technology with a large focus on the recent development in diesel selective catalytic reduction. This is followed by a section on evaporative emissions; regulations, technology and test results.

The section treating alternative fuels is largely dominated by an extensive review on what challenges ethanol E85 use pose on the emission regulatory system and vice versa and a subsection covering the potential result of an increase from 5% to 10% ethanol in commercial gasoline.

The report is completed with a section on the future world harmonized light vehicle test procedure; current status and future work.

1 BACKGROUND

Sweden has by tradition taken an active part in the progressive work concerning emissions in the European Community and is expected to continue to play a leading part in the future. For this future work a few issues of particular interest to Swedish conditions has been identified. These are

- Low ambient temperature requirement for gasoline/ethanol and possibly diesel cars.
- Evaporative requirements particularly concerning ethanol blended gasoline.
- Future requirements on ethanol cars particularly levels and test procedures regarding hydrocarbon emission.

The keywords being ethanol and low temperature. It has of course its origin in the fact that Sweden is a country with cold climate. This characteristic is shared with the other Nordic countries as well as the Baltic states.
Sweden is also a country with widespread environmental concern among its citizens and through last years legislation the fleet of ethanol cars has grown, largely at the expense of gasoline cars. The number of newly registered cars by fuel the last years is shown in Figure 1. The growing number of ethanol vehicles in Sweden reflects in the number of filling stations that provide E85. In fact all Swedish filling stations are required to provide at least one alternative fuel and most filling stations choose E85. This has made Sweden by far the most ethanol friendly country in the EC. The number of E85 filling stations by country is presented in Table 1.

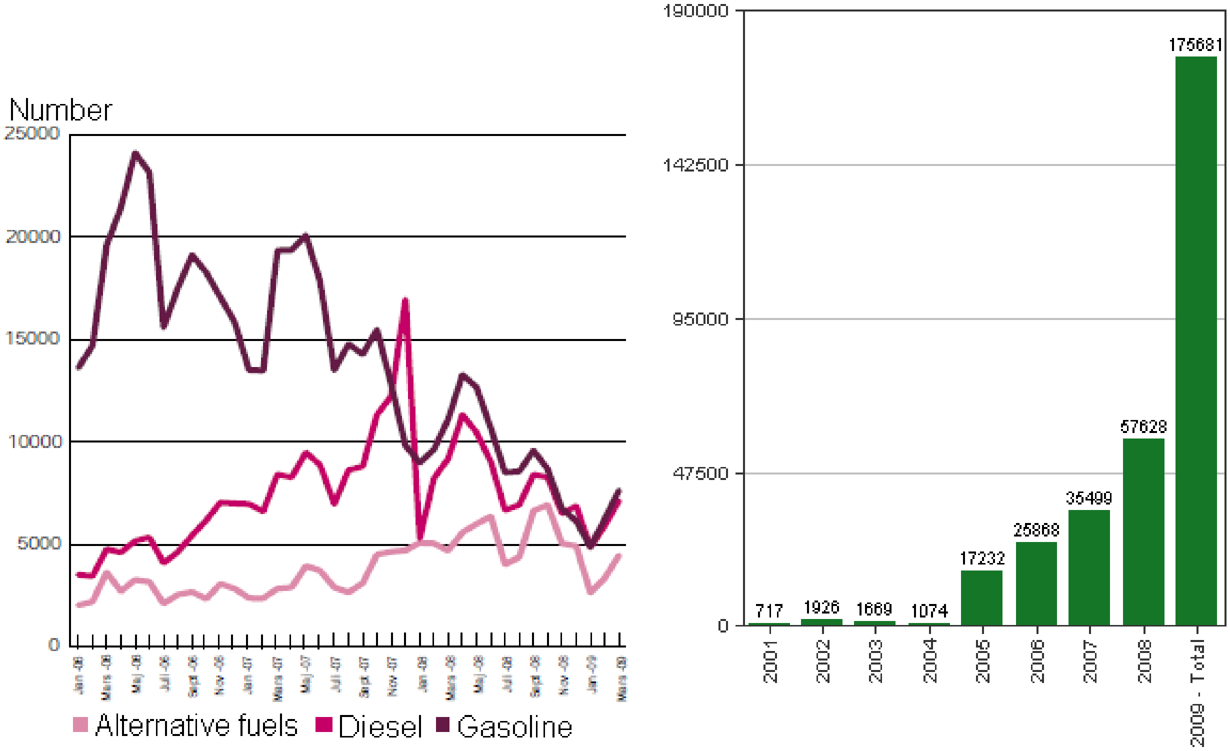


Figure 1 New Swedish cars by fuel

a) New cars by fuel January 2006- March 2009. [1] *b) New ethanol cars sold 2001-2008 and total.*

Source: BAFF

Country	Number of E85 filling stations
Sweden	1557
France	318
Germany	307
Switzerland	62
Ireland	34
United Kingdom	21
Finland	6

Table 1 Number of filling stations that provide E85 in some EC countries

The aim of this report is to shed some light over the identified areas of interest and some adjacent matters. Some areas are briefly covered while others are covered more in depth. This is meant to reflect their relative importance in relation to the Swedish quest. While every journey have to start somewhere this will start with some numbers to characterize the Swedish passenger car fleet.

1.1 The Swedish passenger car fleet

The Swedish car fleet is growing both in number, weight and performance. In the last ten years the number of cars has increased 14%, the average car weight has increased by 10% and average engine power by 19%. Meanwhile the average car age has remained rather constant in the same period, see Figure 2 and evenly distributed between age groups as described in Table 2.

Age years	Number	Percentage
0-4	1 242 819	29.0
5-9	1 361 145	31.8
10-14	898 395	21.0
15-	776 636	18. 2
Total	**4 278 995**	**100.0**

Table 2 Passenger cars in Sweden 2008/2009 by age. [1]

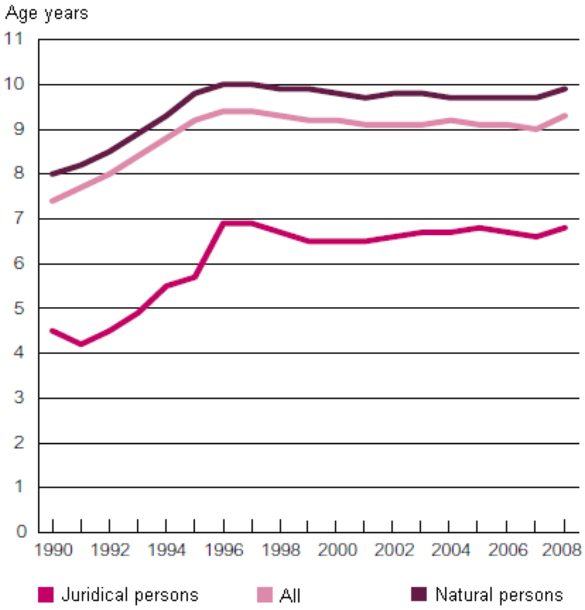


Figure 2 Average car age. [1]

The number of cars per capita Sweden is right on the European average, see Figure 3, together with Spain, Belgium, Lithuania and the UK. It is almost three times as many as in Rumania and one third less than Luxemburg, the least and most car dense countries in the EC.

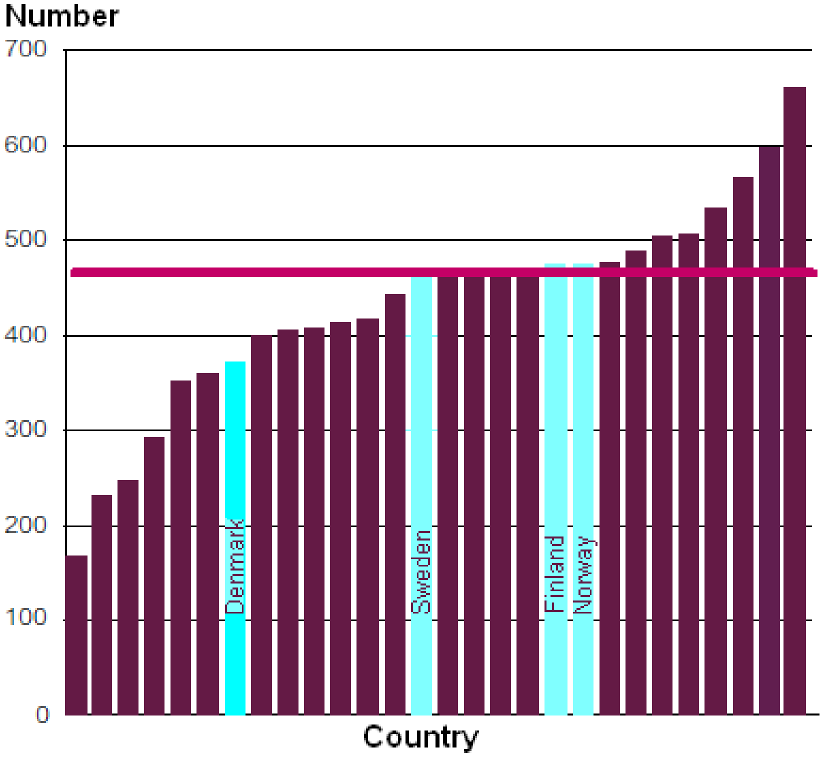


Figure 3 Cars per 1000 population in Europe.

The annual average travelled distance per car in Sweden is approximately 15000 km according to [1]. The distribution in 1999 is shown in Figure 4.

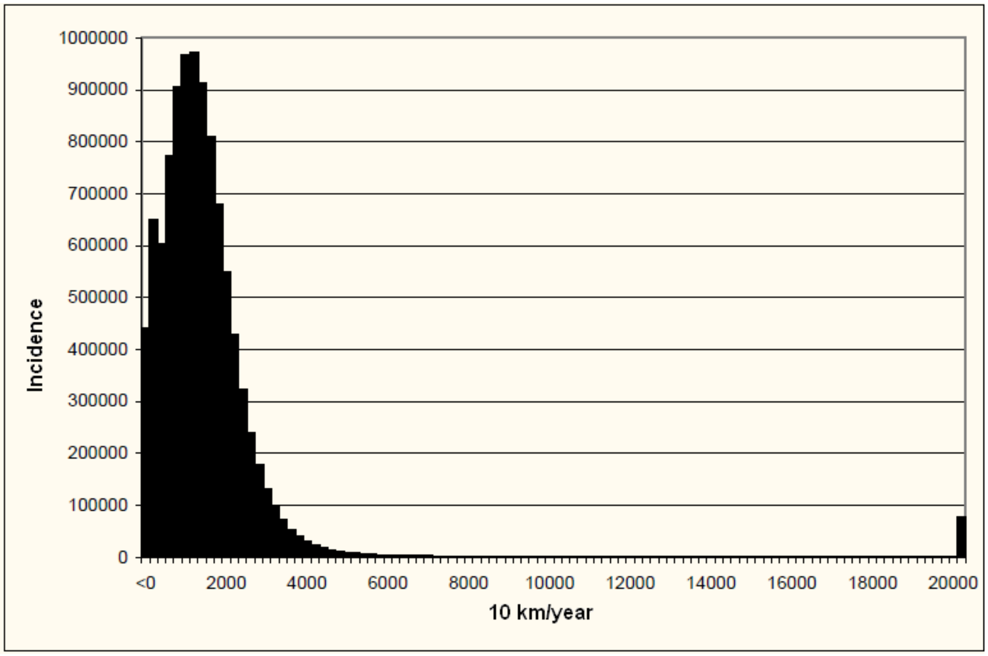


Figure 4 Annual travelled distance distribution

2 THE CHALLENGES OF A COLD CLIMATE

The global average annual temperature is about 14ºC. In Sweden the same figure was 2.9ºC between 1961 and 1990, the Swedish temperature reference period. Since the last two decades the average temperature has increased slightly, presumably as a result of global warming and the average temperature in 2009 was 4.2ºC. Roughly one quarter of Sweden experience subzero average annual temperature.

The annual average temperature in Europe average about 10ºC. In contrast to this European emission test procedures require a test ambient temperature of 20-30ºC. It can of course be argued that most cold starts and drives take place on during the relatively warmer hours of the day and only a few during the night. Still, this does not motivate a discrepancy of the present magnitude.

2.1 Low temperature engine operation

Cold ambient conditions pose several problems to combustion engines and their subsystems. During an investigation carried out in Leeds the effect of ambient temperature on emissions from SI engines was studied. It was shown that on road engine cooling liquid and lubrication oil warm up time and TWC light off time increase by 60-90% during winter conditions (close to 0ºC) compared to summer conditions while driving in a pattern similar to the ECE-15 cycle, see Figure 5. In the case of congested traffic warm up time increase further because of the low power output.

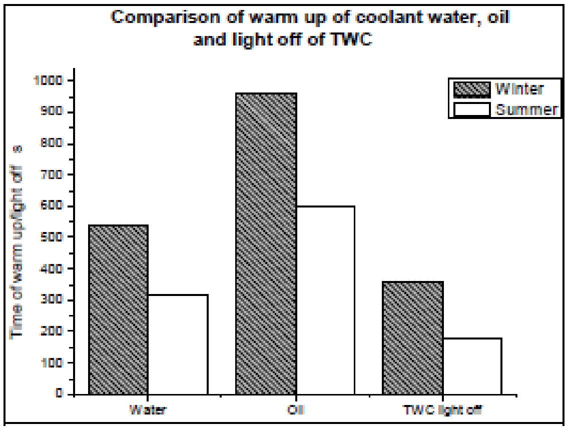


Figure 5 The effect of season e.g. ambient temperature on the warm up time of coolant liquid, lubricating oil and TWC light off time. "Winter" refers to -2ºC and "Summer" to 31.5ºC.[2]

Other authors have reported that engine oil, exhaust gas and engine coolant temperature reach normal levels after approximately 10 minutes of running following a cold start at winter conditions.

The increase in lubricating oil viscosity at low temperature leads to reduced pumpability and higher mechanical losses. Battery performance is reduced at low temperature and fuel volatility is decreased resulting in poor air fuel mixing and ignition problems [3]-[4]. To overcome the problem with fuel volatility the fuel-air mix is often made very rich. As a consequence HC and CO emissions increase. Continuous and repetitive operation in cold conditions is likely to increase the aging of the TWC mainly because of soot accumulation on the active surface of the catalyst.

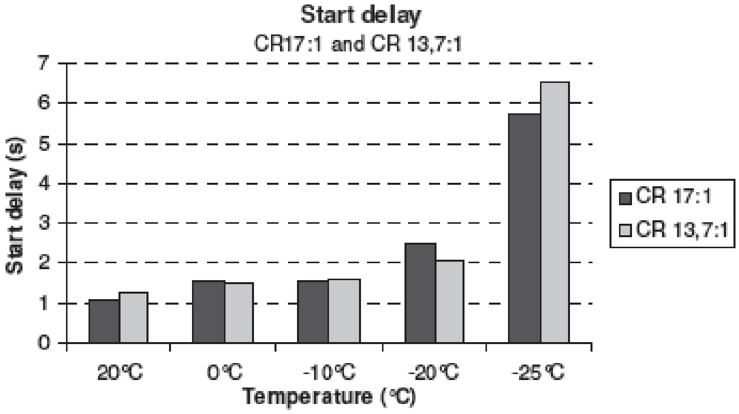
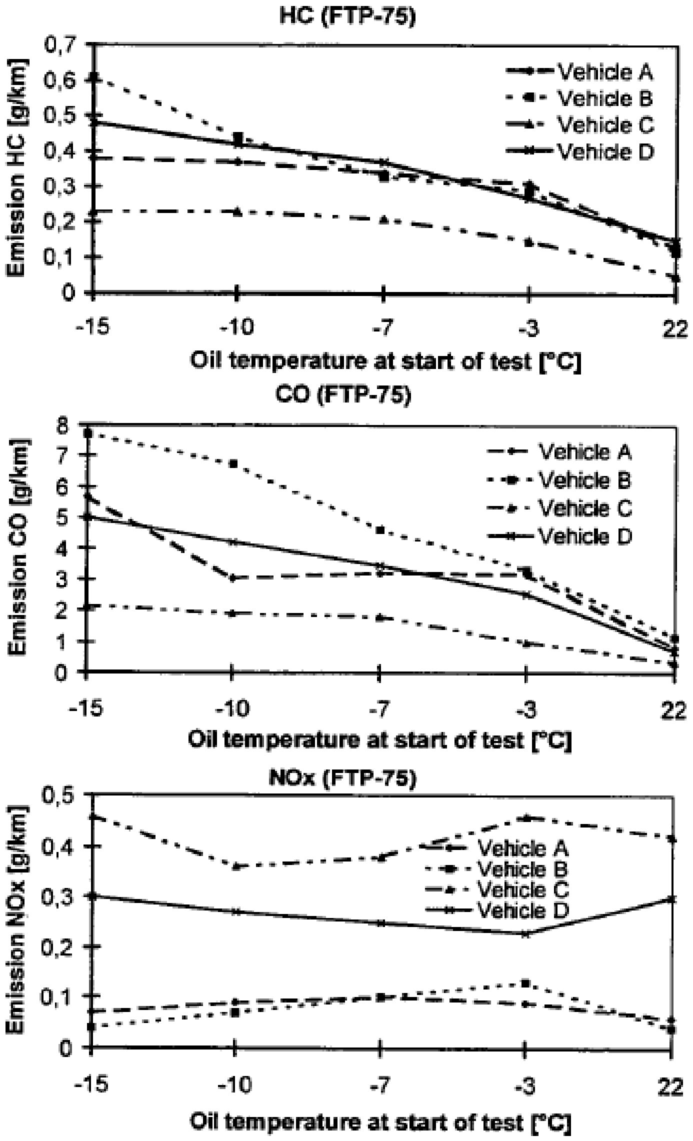
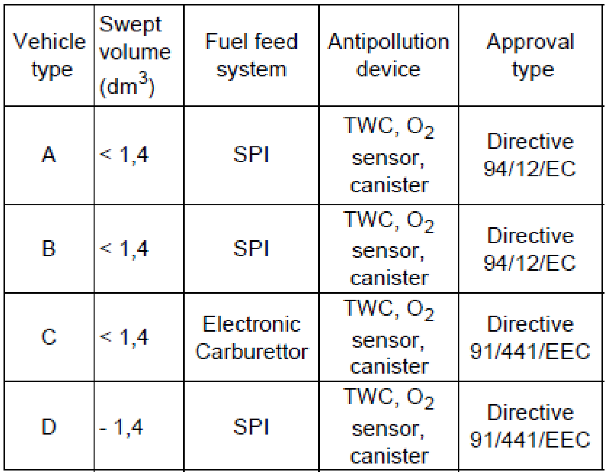


Figure 6 Start delay at different temperatures.[6]

Especially compression ignition engines suffer from start delay as a result of insufficient charge temperature. CI engines depend on compression heat to ignite the charge. In cold operation the available heat might not be sufficient for the charge to ignite. Also, spray cone angle and spray penetration significantly decreases at winter temperatures, driving to a quite poor atomization and spray quality [5]. This behaviour can be explained due to the higher viscosity and lower level of turbulence. Figure 6 show how the start delay of a LD diesel engine available in for instance





Vehicle type	Swept volume (dm^3)	Fuel feed system	Antipollution device	Approval type
A	< 1,4	SPI	TWC, O_2 sensor, canister	Directive 94/12/EC
B	< 1,4	SPI	TWC, O_2 sensor, canister	Directive 94/12/EC
C	< 1,4	Electronic Carburettor	TWC, O_2 sensor, canister	Directive 91/441/EEC
D	- 1,4	SPI	TWC, O_2 sensor, canister	Directive 91/441/EEC

Figure 7 Emission for four vehicles conditioned at various temperatures between -15 and 22°C. [3]

Citroën C5 and Peugeot 407 vary with ambient temperature. The delay is here ascribed to penalties in fuel vaporization and auto ignition capabilities.
Fuel enrichment during start up and incomplete combustion add to increased carbon monoxide and hydrocarbon emissions [6].

Figure 7 show measured emissions for four new vehicles manufactured in the mid 1990:ies. The increase in hydrocarbons and carbon monoxide is evident [3]. More low temperature emission data on SI engines is shown in Figure 8.

2.2 Diesel emissions at subzero temperatures

Regulated emissions from diesel engines have been thought to be more or less insensitive to temperature. Hence, Euro 5 does not require low temperature testing of vehicles with compression ignition engines. With the increasingly strict emission regulation however it might be time to drive CI engine manufacturer to work with low temperature emissions.
In Figure 8 below, NOx emissions from two light duty diesel cars over NEDC is compared to cars operated on other fuels [8]. Both diesel cars fulfilled Euro 2 emission limits where no restriction of NOx were set. It is clear from the figure that NOx emission from the diesel cars are high compared to the other vehicles and, in fact not entirely insensitive to temperature. It is however unclear whether the EGR-system was active at the lower temperatures, see subsection 3.4.
Compared to the other vehicles presented in Figure 8 the diesel cars have low levels of hydrocarbon emissions. There seems to be little difference between 23ºC and 5ºC. The impact of subzero ambient temperatures is however relatively large, most likely as a result of start delay and poor in-cylinder air-fuel mixing as described in the previous section.
Figure 8 also shows particle mass emissions from the same cars. Euro 2 state a maximum PM emission limit of 0.08 g/km. For both cars the PM was found to increase as the temperature decreased at cold start. The effect diminished as the engine warmed up. With the IDI car the PM emissions increase as the temperature

decreased in the beginning of the test but with warmed-up engine the opposite was seen.
As for the particle number and size the particle number seems to increase and the size seems to be shifted towards larger particles as shown in Figure 9.

	TDI	**IDI**	**MPI**	**G-DI**	**FFV**	**CNG**	**LPG**
Model year	1996	1999	2001	2002	2002	1998	2001
Fuel	Diesel	Diesel	Gasoline	Gasoline	E85	CNG	LPG
Emission class	Euro 2	Euro 2	Euro 3	Euro 3	Euro 3	Euro 2	Eurro 3
Emission control	EGR	EGR	TWC	Catalyst	TWC	TWC	TWC
Mileage, km	33800	114000	6420	6300	9500	10140	20400

Table 3 Characteristics of the light duty vehicles referred to in Figure 8

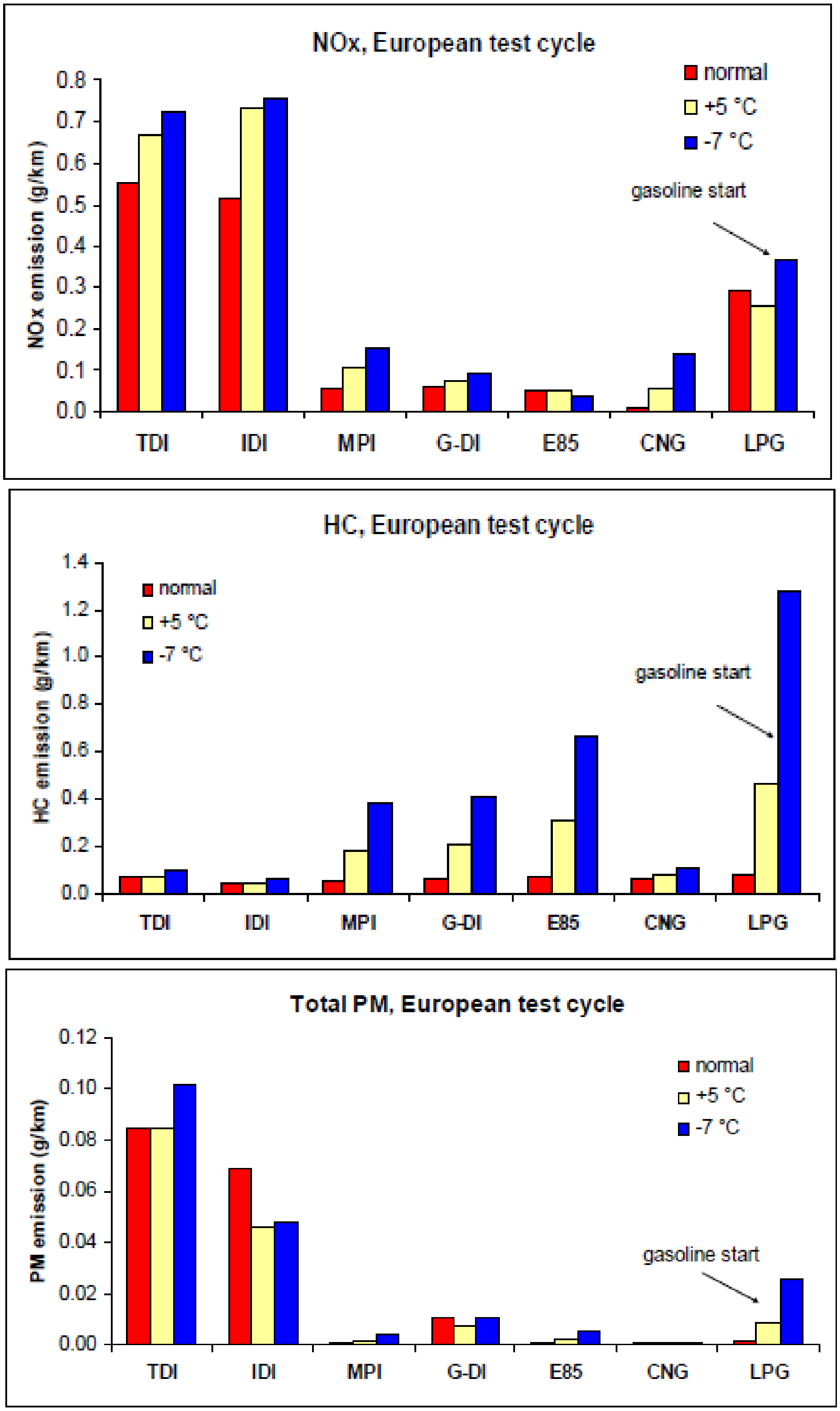


Figure 8 NOx, PM and HC emissions over NEDC from vehicles with different fuels at different temperatures. "Normal" temperature refers to 23ºC. TDI and IDI were operated on

EURO2000 diesel, MPI and G-DI were operated on gasoline fulfilling 98/70/EC. [8]

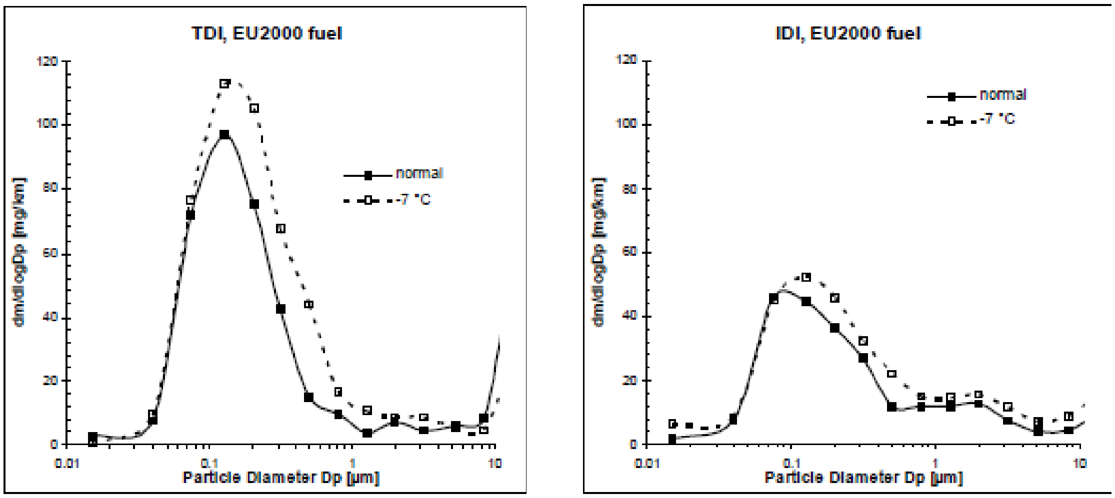


Figure 9 Particle number and size. "Normal" temperature refers to 23ºC. [8]

2.3 Low ambient temperature test procedures

European certification regulation, dictated by Annex 8 of [9] require cold start emissions tests at subzero ambient temperature only for vehicles with positive ignition engines. The test sequence is described in Figure 10.

Before the test is run the vehicle is allowed to soak for at least 12 hours at an ambient temperature of -7ºC. Before year 2000 the engine was allowed a period of 40s idling before sampling started but that period has now been eliminated.

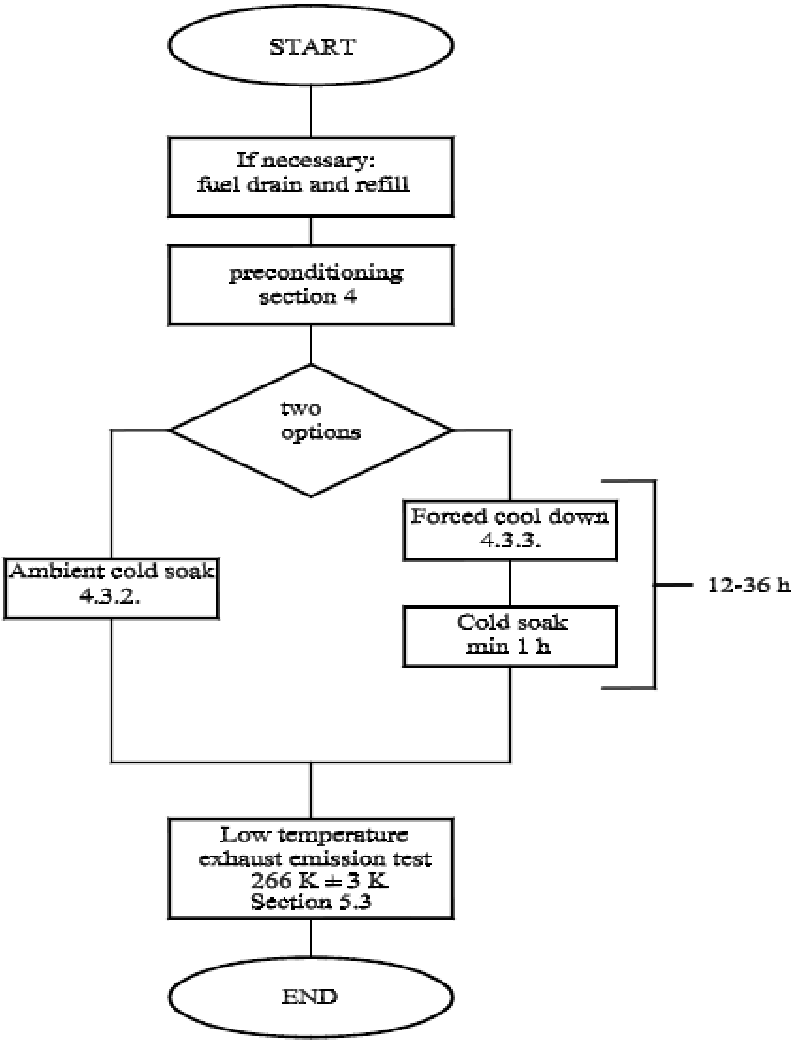
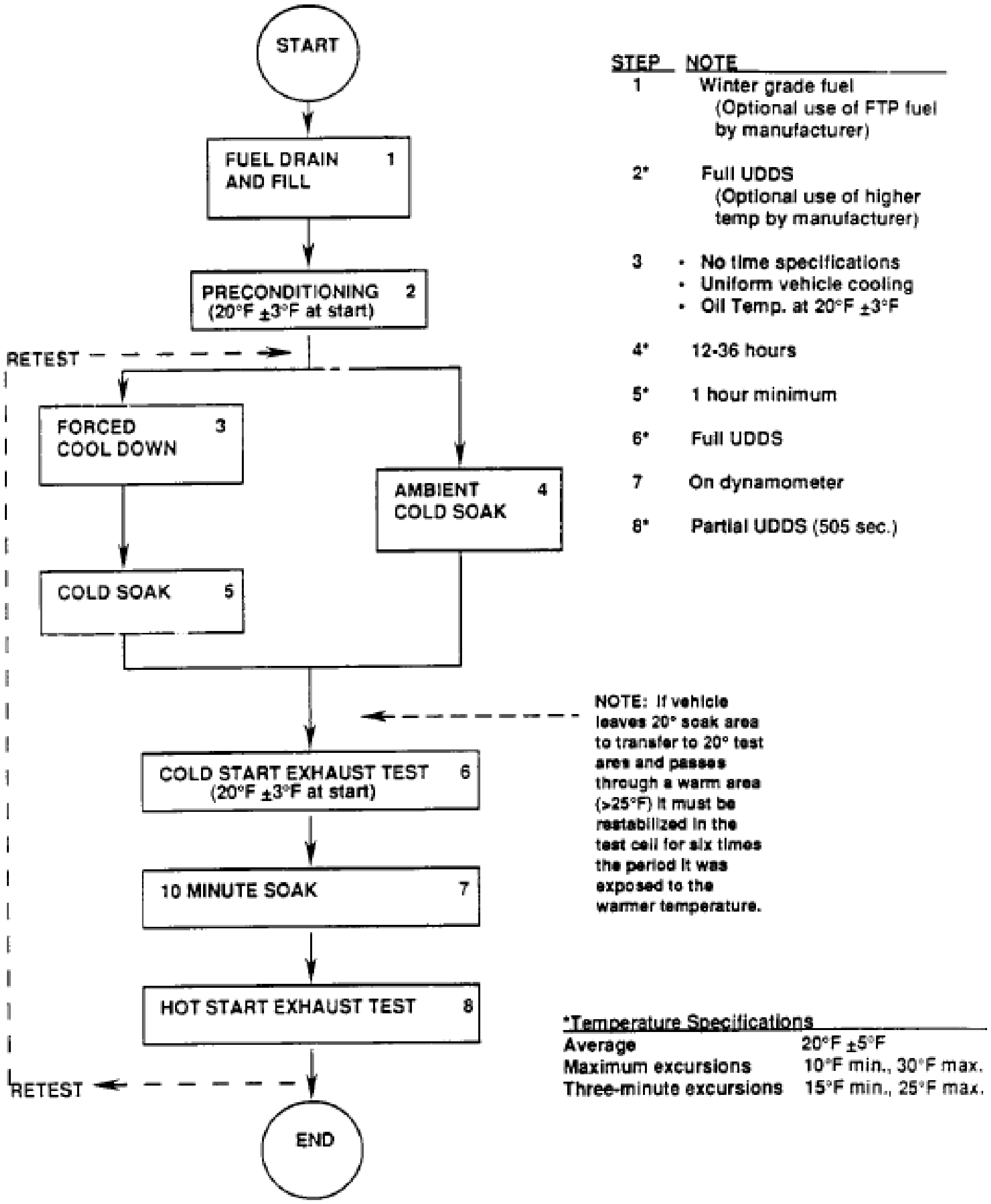


Figure 10 European cold ambient temperature test sequence. Annex 8, §3 of [9]

In USA the corresponding regulation, Subpart C of [11], require subzero ambient temperature emission tests of gasoline fuelled, light duty vehicles and trucks. Beginning 2011 diesel vehicles will however be subjected to the low temperature fuel economy test. The test sequence is similar to that of the European test and can be reviewed in Figure 11.

The details of the two test procedures are compared in Table 4.



STEP	NOTE
1	Winter grade fuel (Optional use of FTP fuel by manufacturer)
2*	Full UDDS (Optional use of higher temp by manufacturer)
3	• No time specifications • Uniform vehicle cooling • Oil Temp. at 20°F ±3°F
4*	12-36 hours
5*	1 hour minimum
6*	Full UDDS
7	On dynamometer
8*	Partial UDDS (505 sec.)

NOTE: If vehicle leaves 20° soak area to transfer to 20° test area and passes through a warm area (>25°F) it must be restabilized in the test cell for six times the period it was exposed to the warmer temperature.

*Temperature Specifications	
Average	20°F ±5°F
Maximum excursions	10°F min., 30°F max.
Three-minute excursions	15°F min., 25°F max.

Figure 11 US cold ambient temperature test sequence. Subpart C §230-94 of [11]

	Europe [9], [10]	**USA/EPA** [11]
Applicability		
	Vehicles with positive ignition engines	Gasoline fuelled engines LDV and LDT
Preconditioning		
Test fuel temperature	≤16ºC	≤16ºC
Evaporative emission control system	Neither abnormally purged nor abnormally loaded	Neither abnormally purged nor abnormally loaded
Vehicle preconditioning	One NEDC (modal) Test cell temperature must remain relatively constant and may not exceed 30ºC	One FTP-72 (transient) The fuel in the vehicle shall be stabilized at -7ºC±6ºC
Additional preconditioning	May be allowed in exceptional cases.	May be allowed in exceptional cases.
Tire pressure	Not specified	According to tire manufacturer recommendations
Climate control	Not specified	Detailed instructions
Stabilization		
Cold storing	Allowed	Allowed
Time	Not less than 12 h and not more than 36 h prior to test.	Not less than 12 h and not more than 36 h prior to test.
Ambient temperature	shall average -7ºC±3ºC during each hour and shall not be less than/exceed -13ºC/-1ºC	shall average -7ºC±2. 8ºC during each hour and shall not be less than/exceed -12ºC/-1ºC
Force cooling	Allowed	Allowed
Cold soak	Minimum 1 hour	Minimum 1 hour
Low temperature exhaust emission test		
Ambient temperature	-7ºC±3ºC May not exceed/ fall below -4ºC/-10ºC for more than 3 consecutive minutes.	-7ºC±2.8ºC May not exceed/fall below -4ºC/-9ºC for more than 3 consecutive minutes.
Temperature measurement point	The output of the cooling fan	Simple average of test cell temperature
Temperature measurement interval	No more than one minute	No more than one minute
Cycle	UDC	UDDS

Table 4 Comparison between European and US cold start testing

2.4 Low ambient temperature exhaust emission test cycles

The test cycles used for low ambient temperature tests are standard test cycles and are also used for other tests as well as for preconditioning drives. Some characteristic numbers of the cycles are compared in Table 5.

	Distance travelled [km]	**Duration** [s]	**Average speed** [km/h]	**Maximum speed** [km/h]
Elementary cycle	1.01	195	18.7	50
UDC	4.04	780	18.7	50
EUDC	6.96	400	62.6	120
NEDC	11.00	1180	33.6	120
UDDS	12.07	1372	31.5	91.2

Table 5 Some characteristics of driving cycles used for low ambient temperature testing

Europe

The driving cycle used in the European low ambient exhaust emission test is known as the new European driving cycle or NEDC. It consists of two parts. Part one, the urban driving cycle, is build up from four consecutive elementary cycles. Part two is a high speed cycle known as the extra urban driving cycle. The time-speed trace of the combined cycles is shown in Figure 12.

The second part was added to account for aggressive, high speed driving. Maximum speed is 120 km/s

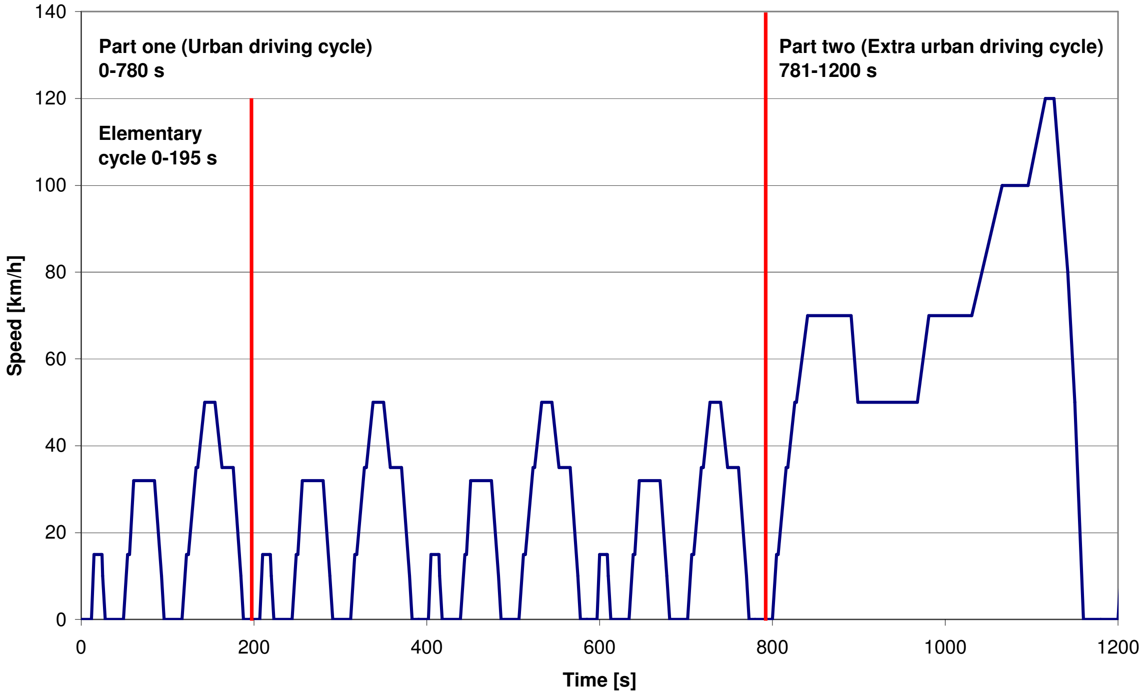


Figure 12 NEDC light duty dynomometer test cycle. UN/ECE Regulation No 83 Annex 4

USA

The urban dynomometer driving schedule – UDDS or FTP-72 is used for emission certification of light duty vehicles in the U.S. and includes two phases:

1. Cold start phase (505 s)
2. Transient phase (864 s)

The first phase begins with cold start. The two phases are separated by stopping the engine for 10 minutes. In the U.S. a weighting factors of 0.43 and 0.57 are applied to the first and second phase, respectively

The cycle simulates an urban route of 12.07 km with frequent stops. The maximum speed is 91.2 km/h and the average speed is 31.5 km/h.

If a pause of 600 s followed by an additional cold stat phase of 505 s is added to the UDDS the over all cycle is known as FTP-75.

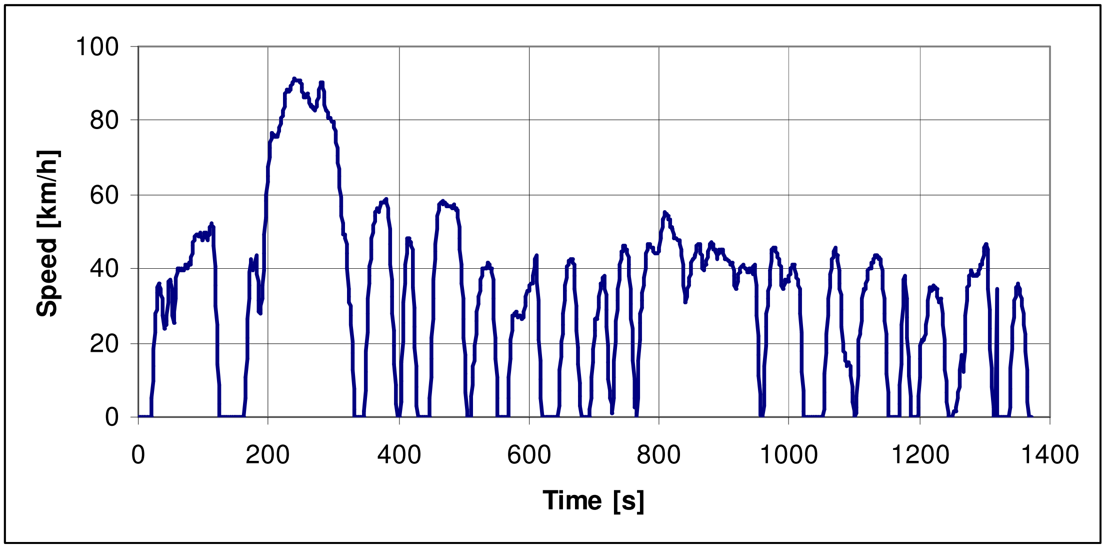


Figure 13 Urban Dynamometer Driving Schedule for Light-Duty Vehicles and Light-Duty Trucks. CFR Title 40 Part 86 Appendix I (a)

3 AFTERTREATMENT SYSTEMS

Aftertreatment systems such as catalysts and particulate filters also suffer to a variable degree from low temperature leaving exhaust emission more or less untreated for a period of time following engine start.

3.1 Three way catalytic converters - TWC

A three-way catalytic converter has three simultaneous tasks:
Reduction of nitrogen oxides to nitrogen and oxygen:

$$2NO_x \rightarrow xO_2 + N_2$$

Oxidation of carbon monoxide to carbon dioxide:

$$2CO + O_2 \rightarrow 2CO_2$$

Oxidation of unburned hydrocarbons (HC) to carbon dioxide and water:

$$C_xH_{2x+2} + 2xO_2 \rightarrow xCO_2 + 2xH_2O$$

These three reactions occur most efficiently when the catalytic converter receives exhaust from an engine running slightly above the stoichiometric point. Within a narrow fuel/air ratio band surrounding stoichiometry, conversion of all three pollutants is nearly complete. However, outside of that band, conversion efficiency falls off very rapidly. The temperature at which a catalytic converter achieves a 50% conversion rate, called the light-off temperature is typically near 250°C.

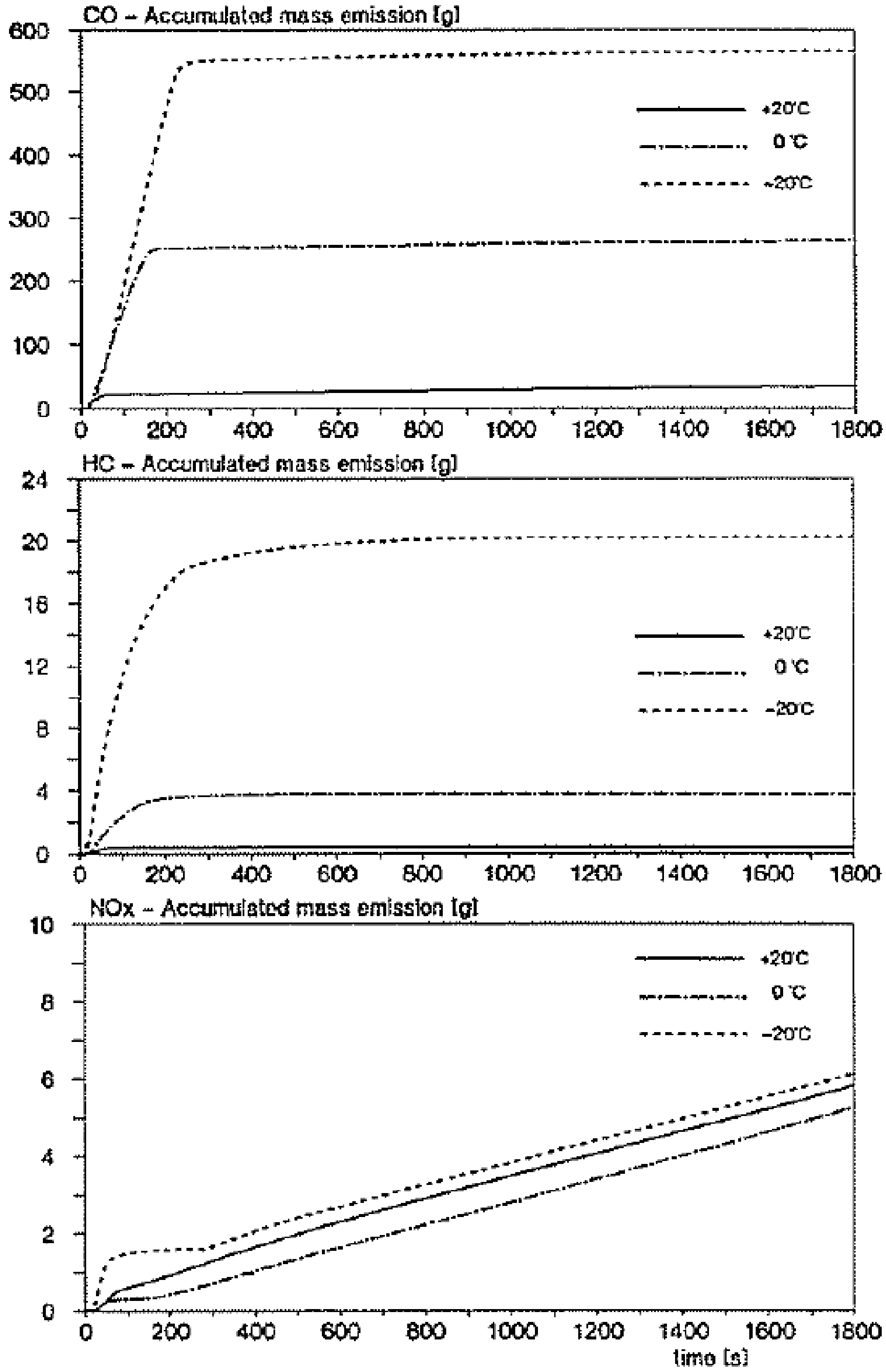


Figure 14 Cumulative emissions from a 2.0 litre fuel injected SI engine equipped with TWC after cold start and at constant load and different ambient temperatures. [4]

In Figure 14 the cumulative emissions after cold start of an early fuel injected engine equipped with a TWC at different ambient conditions is shown. It is clear that once the optimal working conditions in terms of temperature and air-fuel ratio is reached the conversion of CO and HC is very effective. It also indicates the substantial increase in cold start emissions at low ambient temperature.
The results from a more recent study [12] of on-road emissions following cold start at different ambient temperatures are shown in Figure 15. Note that the +4º is a good representative of Swedish conditions and the +21º may represent certification emission test conditions.

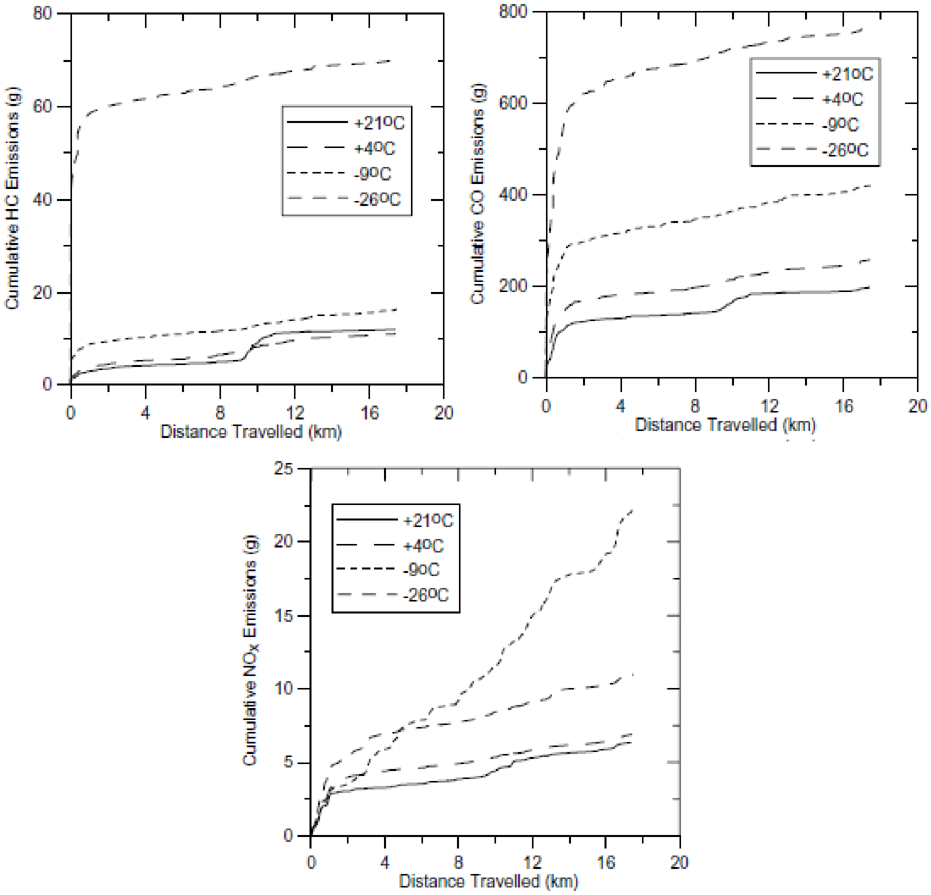


Figure 15 Cumulative emissions over a 17.4 km test route at different ambient temperatures. [12]

3.2 Catalyzed HC traps

One way to address the problem with high HC emission during cold start TWC light-off time is the utilization of a catalysed HC trap. This was studied by for instance[12] -[14], see layout in Figure 16. A catalyzed HC trap is essentially the same as a TWC except that a HC absorbing zeolite has been added under the TWC washcoat that will adsorb HC when the zeolite is cold. Once the catalyzed HC trap heats up the abdsorbed HC molecules will desorb and oxidize to carbon dioxide and water on the TWC surface. The trapping efficiency is dependent on fuel composition but with a catalyzed HC trap cold start HC emissions can be cut by more than 50% [13].

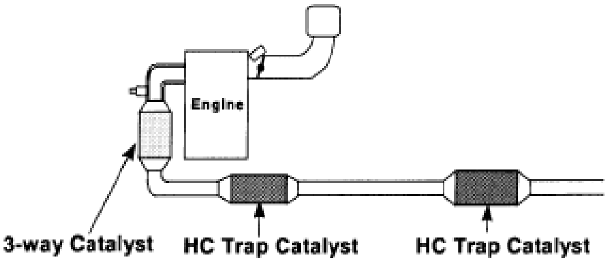


Figure 16 Schematic of exhaust system with catalyzed HC traps. [13]

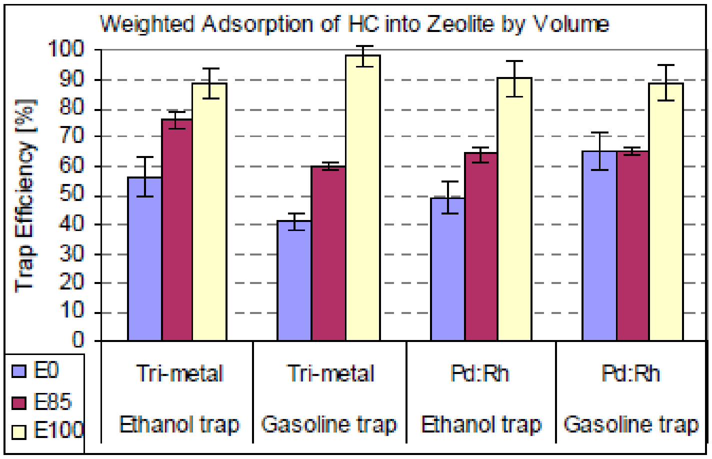


Figure 17 HC trap efficiency. [14]

3.3 Diesel particulate filter - DPF

One of the leading technologies for meeting particulate matter (PM) emission standards is the diesel particulate filter, or DPF [15]. These devices generally consist of a wall-flow type filter, see Figure 18, positioned in the exhaust stream of a diesel vehicle as described in figures Figure 20 and Figure 26. As the exhaust gases pass through the system, particulate emissions are collected and stored. Because the volume of diesel particulates collected by the system will eventually fill up and even plug the filter, a method for controlling trapped particulate matter and regenerating the filter is needed. For many diesel engines, the exhaust gas temperature is insufficient to regenerate the filter. For filter regeneration to work effectively, exhaust temperatures need to exceed about 500° C for non-catalyzed systems [16], and 250° to 300° C for catalyzed systems [17]. Some diesel particulate filters use a passive approach, and do not require an external or active control system to dispose of the accumulated soot. Passive filters are installed mainly on heavy-duty vehicles in place of the muffler. At idle or low power operations, particulate matter is collected on the filter. As the engine exhaust temperatures increase, the collected material is oxidized by the exhaust gas, thus regenerating the filter. To ensure filter regeneration, various strategies are used. Regeneration methods include:

- Periodically raising exhaust gas temperature to above 650ºC where PM oxidation can be self-sustained.
- Installing a DOC (see 3.5) upstream of the filter, again lowering the exhaust temperature needed to burn off the particulates. The DPF is often integrated with the DOC in a single unit as shown in Figure 20.
- Using HC-SCR (see 3.7) to reduce the burn-off temperature of the collected particulates
- Coating the filter substrate with precious metal, thereby reducing the temperature needed for oxidation of the diesel particulate matter.

When the latter method is used the technique is usually called catalyzed (or catalytic) diesel particulate filter (CDPF) or catalyzed/catalytic particulate filter (CPF). The technology reduces particulate matter as well as carbon monoxide and hydrocarbon emissions through catalytic oxidation and filtration.

Figure 18 Diesel particulate filter function and typical appearance.

Independent on method a certain level of exhaust gas temperature is required for the regenerations to occur and hence the DPF can not be regenerated during cold start when PM emission is high. The effectiveness of catalyzed diesel particulate filters is well documented and reduction levels of above 90% is reasonable to expect [17].

3.4 Exhaust gas recirculation – EGR

EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. In a gasoline engine, this inert exhaust displaces the amount of combustable matter in the cylinder. This means the heat of combustion is less, and the combustion generates the same pressure against the piston at a lower temperature. In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture.

Because NOx formation progresses much faster at high temperatures, EGR reduces the amount of NOx the combustion generates. NOx forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature.
Few studies have been done on low temperature performance of EGR system, partly due to the lack of low temperature testing of diesel engines, partly because NOx is not considered a problem at low engine temperature. However, some authors suggest that a high NOx emission level moments after engine start could be caused by poor low temperature performance of the EGR system. It is common practice to disengage the EGR system at low temperatures in order to avoid condensation in the EGR cooler.

3.5 Diesel oxidation catalyst – DOC

Due to the high efficiency of diesel engines and the high volume of excess air diesel exhaust temperatures are very low during normal driving. This has a significant effect on the light-off behaviour of the oxidation catalyst, especially with the large volume exhaust manifolds needed for the recent twin-turbo arrangements. Figure 19 shows an example of the exhaust gas temperature before the turbocharger and DOC of a passenger car engine. With DOC light-off temperature between 150 and 200ºC it takes a considerable amount of time tor the aftertreatment system to begin to work effectively.
In an attempt to address this problem a pre-turbocharger catalyst (PTC) has been suggested [18] and [20]. This is a small oxidation catalyst mounted either in direct vicinity of the exhaust ports or on the exhaust manifold. Due to its low volume and high inlet temperature it has a significantly shorter light-off time than the main DOC and reduces HC and CO with 25-50% and 30-80% respectively [18]- [20] The lower concentrations at the DOC inlet lowers the DOC light-off temperature further reducing the cold start cumulative emissions.

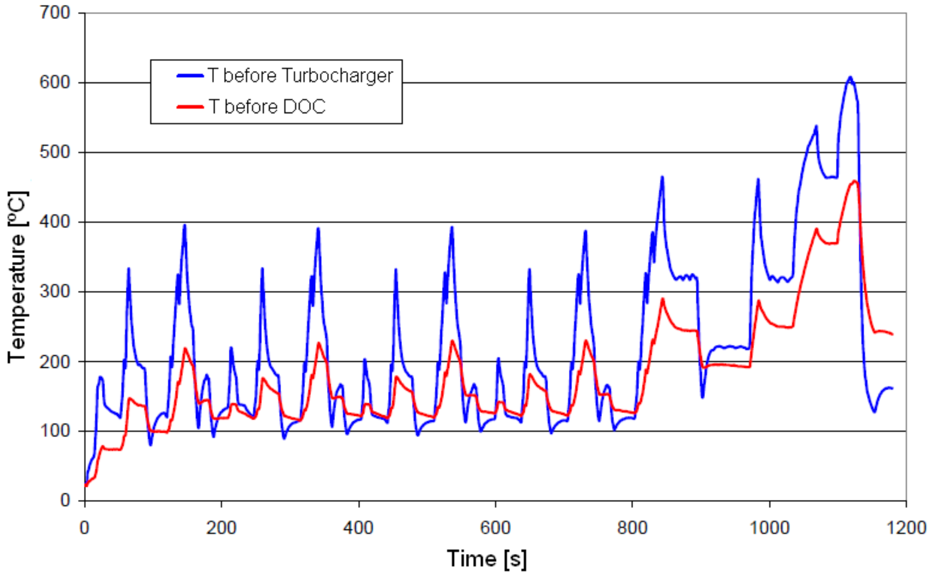


Figure 19 Diesel engine exhaust temperature before turbocharger and DOC versus time since engine start.[20]

3.6 Lean NOx trap – LNT

LNTs contain an oxidative component such as platinum that oxidizes engine-out NO to NO_2 and a storage component (typically an alkali metal salt) that forms a nitrate compound during lean conditions. During rich conditions, the nitrate compound releases NOx that is then reduced to N_2.
LNTs are characterized by a high NOx peak conversion rate but at an operating temperature higher than typically seen in LD diesel exhaust. The temperature span for the necessary 90%+ conversion ratio is also relatively narrow, see Figure 22.

3.7 Hydrocarbon selective catalytic reduction - HC-SCR

HC-SCR is a continuous catalytic reduction of NO_x using unburned hydrocarbons from the combustion or post injection of fuel.
Efficient NO_x reduction is achieved by oxidising NO to NO_2, which quite easily can activate the hydrocarbons. Precious metals have in general high activity for NO oxidation but unfortunately also for oxidation of hydrocarbons. The consequence of a high HC oxidation activity is obviously consumption of the valuable reducing agent with less reduction of NO_2 in the exhaust gas. A solution to this problem could be a catalyst with high activity for NO oxidation to NO_2 and high activity for NO_2 reduction to N_2 with hydrocarbons but with low activity for oxidation of hydrocarbons with oxygen.

3.8 Selective catalytic reduction – SCR

A layout of a typical SCR system is shown in Figure 20. In a SCR catalyst NO_x is reduced ideally to N_2 by means of a reductant agent. There are several formulation for the operation of a SCR catalyst [21]. The first pathway also called the standard SCR occurs according to equation 1.

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \qquad (1)$$

This reaction is relatively slow. A more desired pathway is the fast-SCR reaction characterized by equation 2. This however require equal amounts of NO and NO_2.

$$4NH_3 + 2NO + NO_2 \rightarrow 4N_2 + 6H_2O \qquad (2)$$

A third pathway is shown in equation 3. This is slower than both 1 and 2.

$$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O \qquad (3)$$

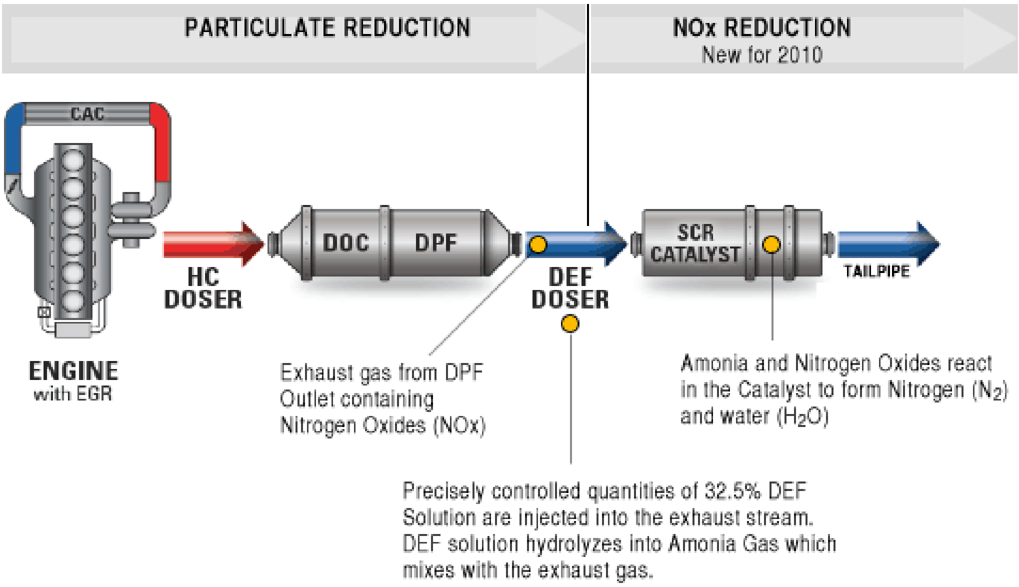
In cases where the NO_2 content exceed the NO content the formation of N_2O has been reported through the two pathways shown in equations 4-5.

$$6NH_3 + 8NO_2 \rightarrow 7N_2O + 9H_2O \qquad (4)$$

$$4NH_3 + 4NO_2 + O_2 \rightarrow 4N_2O + 6H_2O \qquad (5)$$

These are particularly important at intermediate temperatures common for light duty service.

Common to all these reaction is the need for a reductant, ammonia, NH_3 [22]-[26].



Exhaust gas from DPF Outlet containing Nitrogen Oxides (NOx)

Amonia and Nitrogen Oxides react in the Catalyst to form Nitrogen (N_2) and water (H_2O)

Precisely controlled quantities of 32.5% DEF Solution are injected into the exhaust stream. DEF solution hydrolyzes into Amonia Gas which mixes with the exhaust gas.

Figure 20 Schematic of a typical SCR exhaust systems. Light duty vehicles does not usually have both EGR and SCR systems. DEF is the ammonia source, in Europe more known as AdBlue. Source: Buswest.

In automotive applications ammonia is added as a 32.5% urea-water solution with the trade names Adblue® [27] or DEF (for automotive applications) or NOxCare™ (for stationary and marine applications). The ammonia is extracted from the urea solution in three steps. First the water is evaporated releasing the urea. The urea then decomposes into one NH_3 and one $HNCO$ (isocyanic acid) molecule. The next stem is for the $HNCO$ to decompose into one NH_3 and one CO_2 molecule.

Urea decomposition does not reach completion in temperatures typical for light duty diesel engine application. Only about 20% of the urea decomposes to $HNCO$ and NH_3 at 330 ºC and only 50% at 400º. In addition, $HNCO$ has been shown to be very stable and require an oxide surface to catalyze its decomposition to NH_3 and CO_2. This means that, under low temperature conditions almost all urea decomposition occurs on the catalyst surface.

It is suggested that deNOx reaction can take place at temperatures under 300º by utilizing NH_3 and $HNCO$ stored on the catalyst. Modern state of the art SCR catalysts can exceed 90% conversion rate at catalyst inlet temperatures above 300ºC. Below 300ºC the conversion rate deteriorate rapidly with only 60% conversion rate at 200º. A typical temperature-conversion rate chart is shown in Figure 21. [22]-[26]

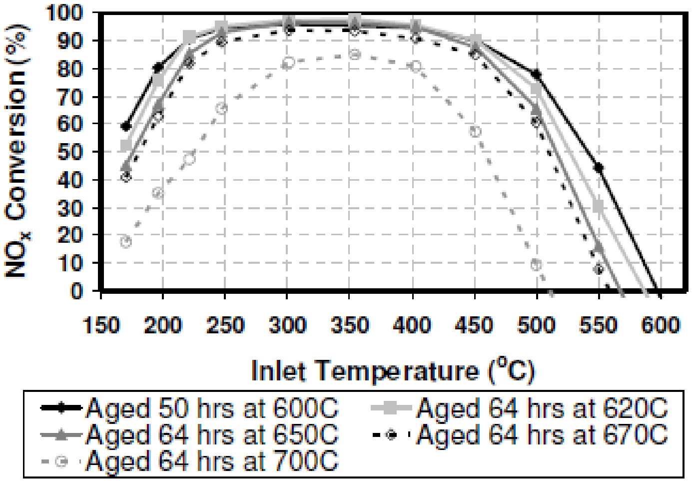


Figure 21 NOx conversion ratio versus SCR inlet temperature for an extruded vanadium SCR. [24]

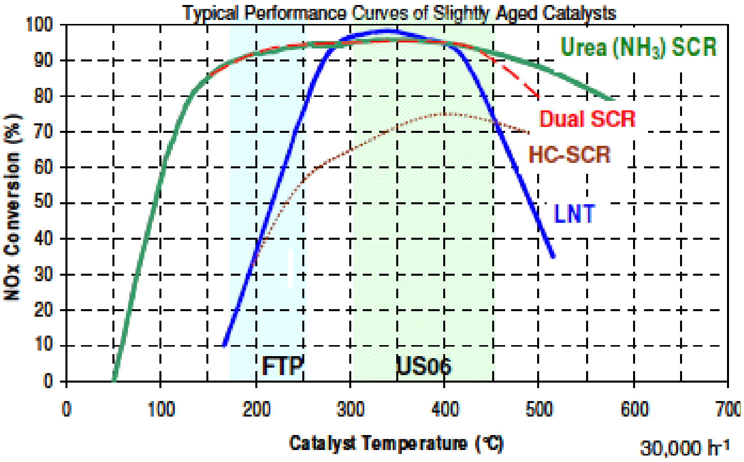


Figure 22 Typical temperature operating range for SCR compared to other systems.[25]

3.8.1 Effect of long term storage of AdBlue®

AdBlue® is a 32.5% solution of urea in water. Urea is a stable agent but when dissolved in water hydrolyzes very slowly to ammonium carbamate and eventually decomposes to ammonia and carbon dioxide [28]. Shelf life when stored appropriately at a temperature below 25ºC is at least 18 months [27]. Storage at temperatures above 35ºC speeds up hydrolyzation and vapourization which impairs shelf life significantly, see Table 6.

When stored at temperatures below -11ºC AdBlue® will solidify. Fortunately the density of the solid phase is slightly lower than that of the liquid phase which means that frozen AdBlue® will float. Long term storage at low temperature may pose problems with precipitation and completely solidified AdBlue® should be warmed up carefully to avoid crystal precipitation. Completely solidified AdBlue® stored at temperatures below -11ºC has approximately 7% larger volume than liquid solution. Therefore there is a risk of bursting of fully filled containers [29].

Max. constant storage temperature [ºC]	Min. shelf life [months]
≤10	36
≤25	18
≤30	12
≤35	6
>35	Significant loss of shelf life

Table 6 AdBlue shelf life as granted by supplier and depending on storage temperature. From manufacturer datasheet.

3.8.2 Ammonia slip

Ammonia, NH_3 slip can be described as NH_3 that exits the SCR catalyst unreacted [30] Three causes of NH_3 slip has been identified:

1. Incomplete SCR reaction
2. Release of stored NH_3
3. Incomplete conversion of injected urea

From a low temperature operation view number 1 and 3 are of most concern. unreacted NH_3 can react with sulfuric acid and water in the atmosphere enhancing the rate of aerosol formation. In exhaust systems fitted with a catalytic diesel particulate filter CPDF NH_3 is generally removed at temperatures above 200ºC and large amounts of N_2O and NO_x can be formed rendering a significant reduction in the overall NO_x reduction level. The levels of N_2O and NO_x formed is strongly dependent on the presence of NO as indicated by Figure 23.

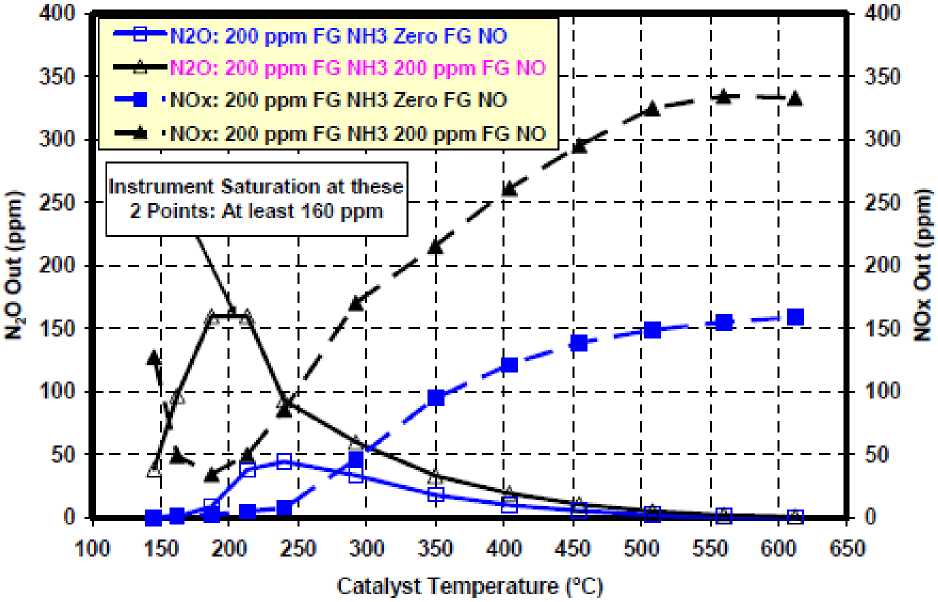


Figure 23 Conversion of NH_3 over a CDPF [30]

As a means of reducing NH_3 slip a NH_3 slip catalyst can be utilized. This is designed for selective oxidization of NH_3 into N_2 and H_2O. Experiments have shown that a NH_3 slip catalyst can reach conversion rates exceeding 90% at catalyst temperatures above 250ºC. However, below this light-off temperature conversion rates deteriorate rapidly [30].

3.8.3 Managing AdBlue® feeding systems at subzero temperature

AdBlue® is a eutectic mixture of urea and water which means that the freezing point is at its lowest, see Figure 24. It takes days for the urea in a normal sized tank to completely solidify even at temperatures as low as -20ºC [31]. Still, for many market a system to deal with the freezing point at -11ºC is required during winter operation. The US market BMW 330d utilizes two urea tanks for that purpose: a heated, 1.6 gallon “active” tank, and a 4.5 gallon “passive” tank. This arrangement allows to minimize the energy used for heating of urea solution in cold weather operation, and provides more flexibility in incorporating the tanks onto the vehicle. The urea solution from the active tank is delivered to the exhaust system through a heated piping system and injected upstream of the SCR catalyst using a dosing valve.
A NOx sensor downstream of the SCR catalyst provides feedback on the concentration of NOx in the exhaust emissions. The average driving range provided with the supply capacity of the two urea tanks is sufficient to have the urea solution replenished only when the driver needs to change the engine oil.

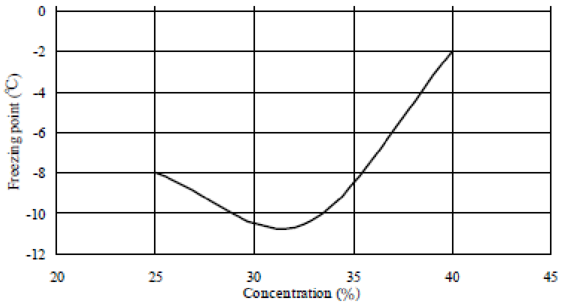


Figure 24 Influence of concentration on freezing point. [23]

A platform with Inergy's DiNOX system applied to a BMW 330d has been tested at winter conditions (-15ºC and -30ºC) in Arjeplog [31]. A 4 liter tank of fully solidified urea was thawed by the 90W in-vehicle urea heating system at -15ºC and -30ºC. The urea consumption was approximated to be 100 ml/hour. The result from the test is shown in Figure 25. Although considerable time is required to thaw the entire tank at -30ºC the thawing rate exceeds the consumption rate in the long perspective. Nothing was mentioned about the time lag between engine start and first urea delivery to the exhaust pipe.

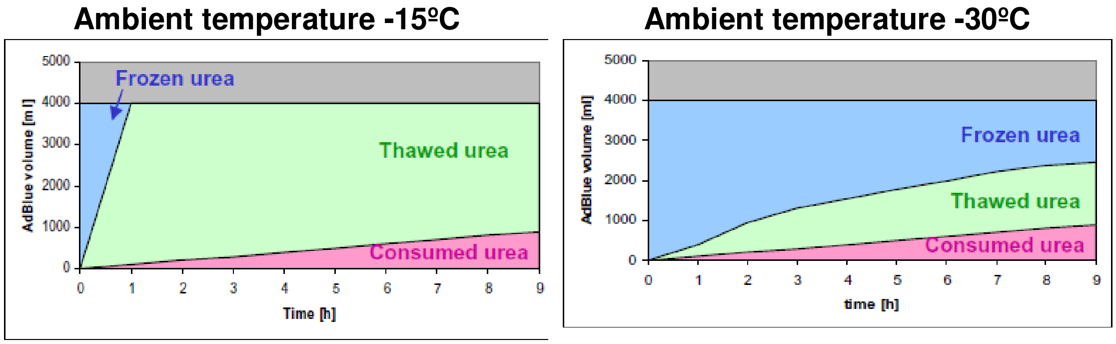


Figure 25 Thawing of urea at winter temperatures.[31]

Mercedes E320 CDI has only one urea tank with integrated pump and active heater. This defrost concept allow a completely frozen urea tank to start dosing approximately 20 minutes after engine start as demanded by EPA.

3.8.4 Mercedes BLUETEC™ SCR system

A schematic of the Mercedes BLUETEC™ SCR exhaust treatment system [32] is shown in Figure 26. It begins with the engine itself which is optimized primarily for performance and fuel efficiency. Next is a diesel oxidation catalyst and a particulate filter and finally a SCR catalytic converter. Upstream of the SCR catalyst is the urea dosing valve directly installed in the exhaust pipe. The dosing valve is air cooled and therefore lacks return lines for packing reasons. The urea line goes in underfloor position. The system also involves additional temperature sensors for controlling the

DOC and SCR temperature as well as NOx-sensors for controlling urea dosing strategy and diagnostic tasks. In addition there are self learning functionalities for adapting the dosing strategy to ensure maximum deNOx performance.
A fast light off combustion strategy has been developed. With this calibration start of NOx conversion is reached within the first 250 seconds of the FTP75 test cycle.

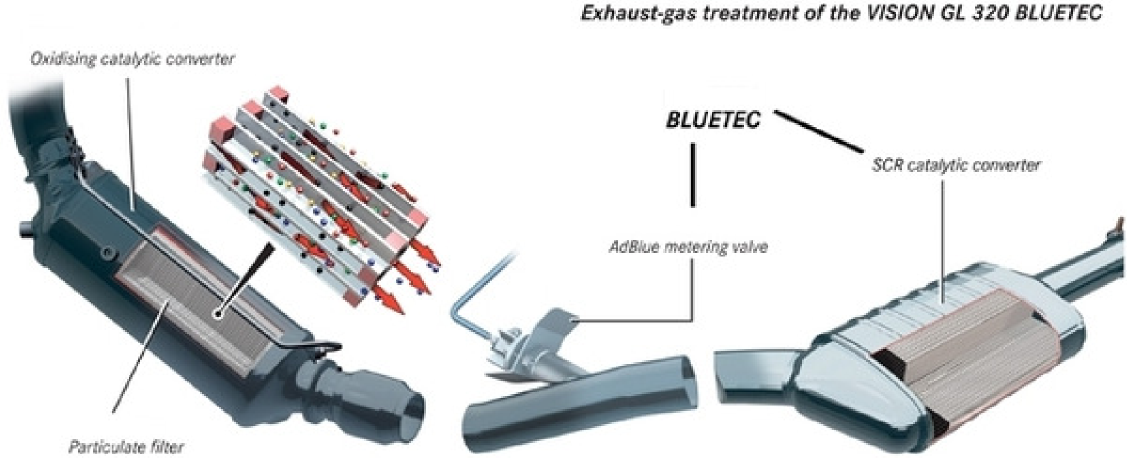


Figure 26 Mercedes BLUETEC™ SCR system. Source: Mercedes

3.8.5 Chrysler Dodge Ram

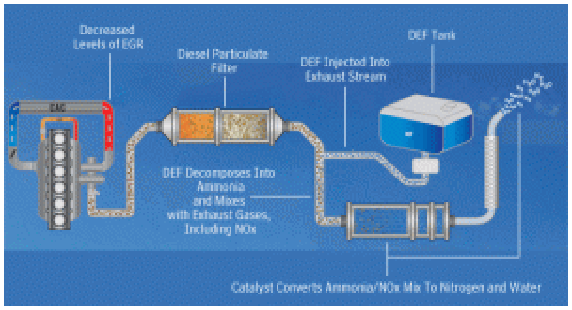


Figure 27 Schematic showing the Chrysler Dodge SCR system

A schematic of Chrysler Dodge SCR system is shown in Figure 27 and a photo showing some of the components is found in Figure 28. Chrysler use engine coolant to keep the urea injector at an optimal operating temperature. Engine coolant is also run through lines in the urea tank when sensors indicate risk of freezing. No electrical device is used to heat the urea since they claim that no deNox technique is necessary at very low engine temperature. Urea sensors are installed in the urea tank to monitor the urea quality. They are claimed to be able to discriminate between agricultural and automotive urea. The system incorporating an eight gallon (30 litre) urea tank, lines and SCR hardware weighs less than 100 kg so the payload capacity is not heavily affected. The calculated range of the eight gallon tank is 4000 miles (approximately 6400 km).

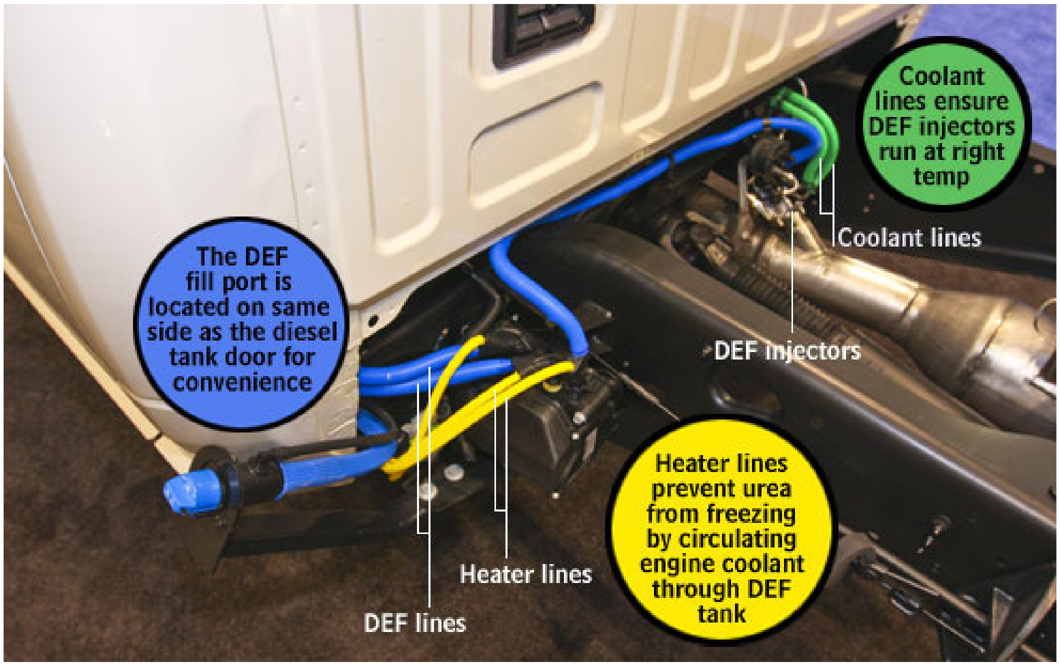


Figure 28 Chrysler Dodge SCR demonstrator. DEF - Diesel exhaust fluid is the US trade name for 32.5% urea solution.

4 EVAPORATIVE EMISSIONS

The recent years exhaust emissions regulations have effectively reduced the HC and VOC (volatile organic compound) emissions through the exhaust pipe. However, this is not the only origin of harmful hydrocarbon emissions from a vehicle. In addition to liquid fuel leaks there are several sources of evaporative emissions from the fuel system. Figure 9 shows a schematic of a fuel system. Some properties of the components of a fuel system are described in 4.4.

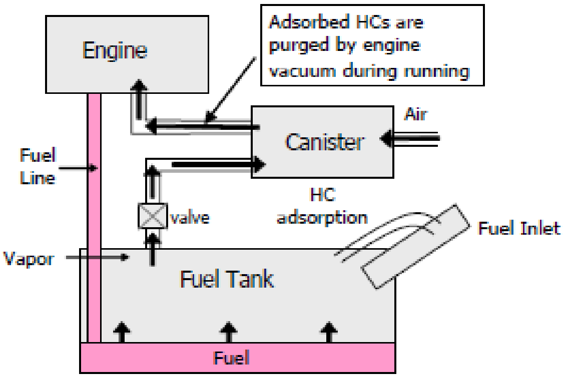


Figure 29 Schematic of canister and fuel system.

4.1 General concepts

There are three main sources for evaporative emissions. Fuel vapour can escape during refuelling, due to permeation through tanks, hoses and other fuel system components and as canister breakthrough. In certification testing the evaporative emissions are evaluated as the amount of hydrocarbons that escape the vehicle evaporative control system during a number of simulated events. These events are diurnal temperature variation, hot soak, running loss and refuelling test.

4.1.1 Evaporative emission sources

Refuelling loss

When pouring fuel into the fuel tank through the fuel inlet the vaporized fuel trapped in the tank will start to migrate through openings in the tank. There are two major strategies to take care of this vapour. In Europe the vapours are recovered by the filling nozzle of gas station fuel pumps while US cars generally are equipped with an onboard refuelling vapour recovery (ORVR) system. The onboard recovery of refuelling vapour demands larger canisters. Still a small amount of fuel vapour may escape during refuelling.

Permeation

The fuel system consists of multiple leads, hoses, valves, pumps and other components. None of these are completely gas proof. When exposed to heat the vapour pressure rise in the fuel system and some of the vapour begins to escape trough joints, seams and through the material itself. This is called permeation.

Canister breakthrough

The canister is usually filled with activated carbon that adsorb fuel vapours from the tank whenever the pressure in the fuel tank increases. When the vehicle is operated, at certain operating points the canister is purged with fresh air by the engine intake manifold suction and the vapours are combusted in the engine cylinders.

At low load the intake manifold suction may not be sufficient to purge the canister which leaves the canister loaded. If a fully loaded canister is subjected to additional strain such as a refuel or heat exposure, the load on the canister reach the canisters maximum capacity. Additional vapours are released and eventually vented out to the atmosphere. This is usually called canister breakthrough.

4.1.2 Evaporative emission tests

Diurnal emission test

The test is designed to simulate an extended parking of up to 72 hours. During a diurnal emission test the vehicle is prepped and parked in a sealed housing for evaporative determination, SHED, for a specified amount of time, usually 1-3 days. The temperature in the SHED is varied to simulate the temperature difference during a day. The temperature profiles of a European 24-hour and a US 72-hour diurnal test are shown in Figure 30. The test procedure for the diurnal test is described in more detail in 4.2.

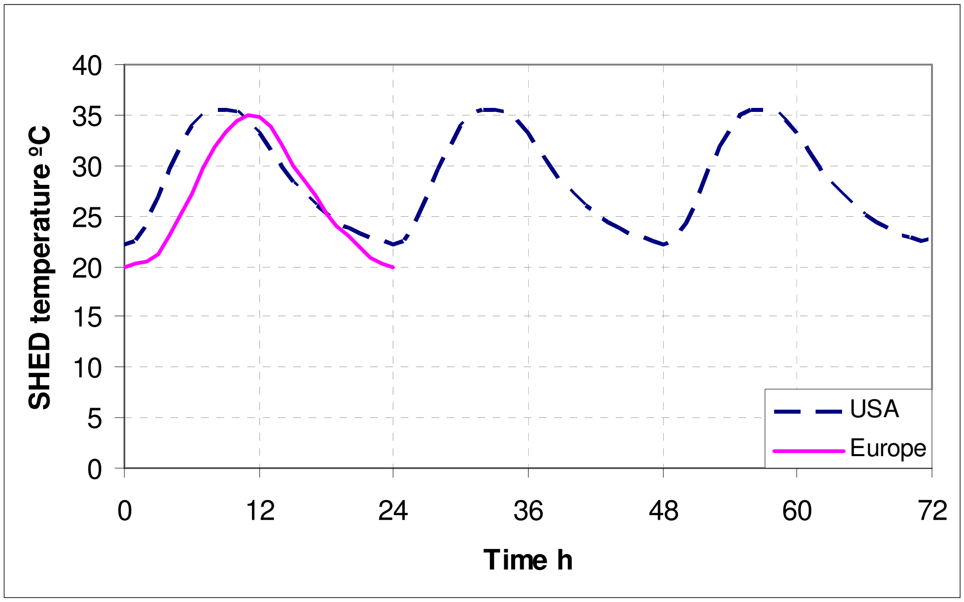


Figure 30 Chart showing a SHED temperature variation during diurnal emission test

Hot soak test

The hot soak test simulates and a short term parking of a warmed up car in hot conditions. Before a hot soak test is carried out the vehicle under test is driven on a chassis dynomometer according to a stipulated driving scheme in order for the engine to reach operating temperature. The vehicle is then parked in a SHED where the evaporative emission measurements take place during a relatively short period of time while the engine and vehicle cool down. The test procedure for the hot soak test is described in more detail in 4.2.

The compliance to the emission regulation is usually based on the combined diurnal and hot soak test results.

Running loss test

This test determines the evaporative loss during a simulated high-temperature urban driving. In the US test procedure the vehicle is operated on a chassis dynomometer through one UDDS, a 2-minute idle, two consecutive New York city cycles (NYCC), another 2-minute idle, another UDDS followed by another 2-minute idle, see Figure 31 for time-speed trace. The ambient as well as the fuel temperature should be 35º±3ºC.

The running loss test is difficult to perform correctly and has no European counterpart.

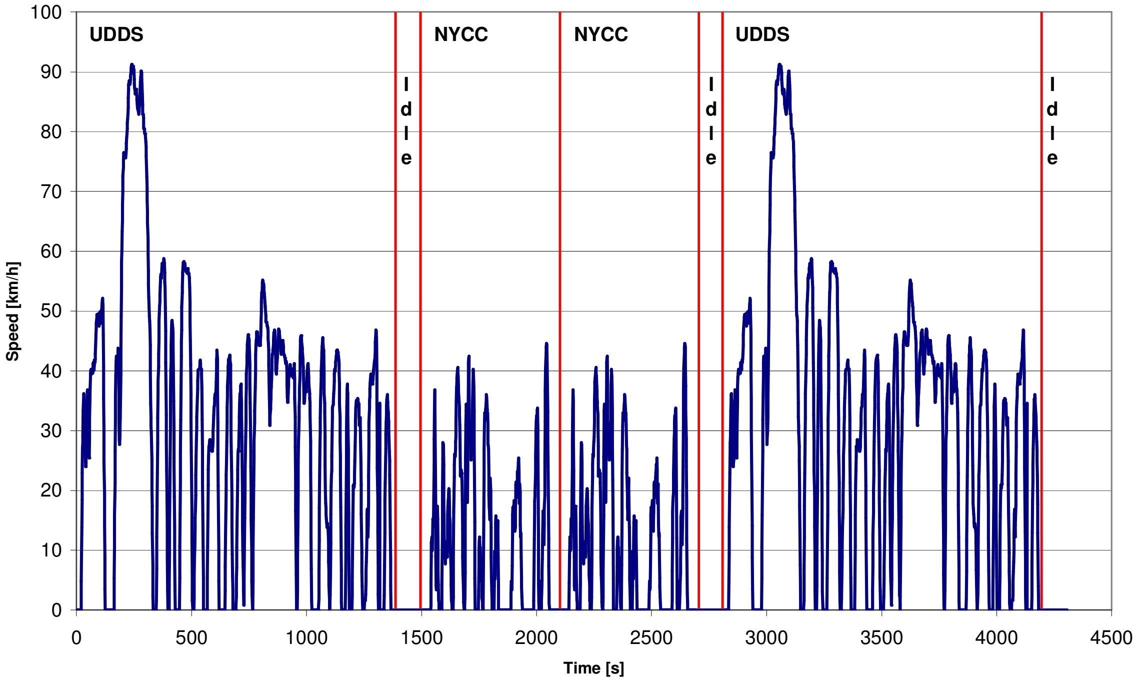


Figure 31 Driving scheme for running loss test.

Refuelling test

This test is used in US to determine the evaporative emissions while refuelling the vehicle. In Europe the refuelling vapours are taken care of by the stationary refuelling nozzle and not by the vehicle itself. Hence there is no European counterpart.

The vehicle is placed in a SHED, the fuel filler cap removed and an initial analysis of the atmosphere in the SHED is performed. the vehicle is then refueled until the refuelling nozzle automatic shutoff is activated. A post refuelling analysis of the atmosphere is performed and the refuelling loss calculated.

Test	Europe	US
Diurnal + hot soak test	1 day: 2.0 g/test	2 day: 0.65 g/test 3 day: 0.50 g/test
Running loss test	N/A	0.03 g/km
Refuelling test	N/A	0.05 g/liter dispensed fuel

Table 7 Evaporative emission standards for LDV [10], [11] §1811-04 and 1811-09. Note that the numbers for diurnal + hot soak test differ from those in Table 12 since the latter apply to model year 2007 cars.

4.2 Test procedures for diurnal and hot soak test

There are at least three test procedures available for evaporative emissions testing, one for the EC countries and two for the United States. Using these procedures the evaporative emissions created in a vehicles fuel tank and system can be measured as a mass of hydrocarbons (HC). For the US a federal procedure regulated by the Environmental Protection Agency (EPA) is used alongside with a procedure for the state of California regulated by the State of California Air Resources Board (CARB). Several other US states have adopted the CARB standards, some states are also considering to adopt these standards. EPA and CARB now accept certification data generated using the other agency's test procedure. These test procedures are applicable to all gasoline-, liquefied petroleum- and alcohol fueled passenger cars, light-duty trucks, medium-duty vehicles, heavy-duty vehicles, hybrid electric vehicles and motorcycles. These test procedures do not apply to vehicles that are exempt from exhaust emission certification.

4.2.1 Description of the test procedures

The three test procedures show extensive similarities. They all consist of a preparation of the vehicles fuel system including fuel fill specific reference fuels to 40% of the tank capacity of the vehicle in question and a carbon canister fill to breakthrough. A gas mixture with the consistency of butane and nitrogen 50/50 is used to load the canister. A subsequent stabilization in a temperature controlled environment, so that the fuel system has time to adapt to the reference fuel is required.

Two different preconditioning drives on a chassis dynamometer with stabilization time between are performed with all test procedures. The purpose of the first preconditioning is to operate the vehicle in road like conditions and to create a purging of the carbon canister. The second preconditioning is done to prepare the vehicle for the immediately following Hot soak test. Differences in the test cycles are described in the following chapter of this report.

The hot soak test that has duration of 60 minutes is performed in the VT-SHED chamber. According to the test procedures, the hot soak must be started within 7 minutes from the end of the preconditioning drive and a maximum of 2 minutes after engine shut down. The vehicle should not be driven into the VT-SHED enclosure because the risk of contamination of the enclosure and the vehicle is therefore pushed into the enclosure. One measurement is performed after 60 minutes An initial measurement is recommended at the start of the measurement sequence to register the background emissions before the start of the test. A soak period of 6-36 hours in a temperature controlled environment is performed before the diurnal test of 24-, 48- or 72 h is started. The soak can be performed in the VT-SHED, though no measurements of emissions are required. The diurnal heat build up can be started after the soak. A measurement to analyze the atmosphere and background emissions in the enclosure is done 10 min. after the beginning of the test. Measurements of the HC level in the enclosure are registered after 24-, 36-, or 72 h, depending on the test time. The highest HC-level from the measurements is valid as the result to the diurnal test.

4.2.2 Differences between the procedures

The two US test procedures have the exact same test sequence. The EC procedure diverges from these with a simpler handling of the vehicles fuel system and carbon canister adaptation. In this sequence the US methods have two fuel fills with the first preconditioning drive between them, while the European procedure prescribes the second fuel handling after the canister fill. The EC procedure however starts with the canister fill. The difference that affects the vehicles fuel system is that when performing tests according to the European procedure both preconditioning drives are executed after the canister fill. The main purpose of the preconditioning drives in all the procedures is to adapt the vehicles fuel system to the reference fuel and the preceding fuel change and to purge the carbon canister.

The preconditioning drives performed on a chassis dynamometer are identical for the US procedures. The first preconditioning drive is called FTP 72, also known as EPA II, UDDS or LA-4. This is a standard city cycle and can be seen in Figure 34. FTP 72 consists of the first two phases of the diagram, the cold start phase and the transient phase.

The second preconditioning that replace the running loss test if only diurnal emissions are measured, is called FTP 75, also known as EPA III. It consists of the two first phases (FTP 72) and a third phase called hot start phase which is identical to the cold start phase. Between the second and the third phase a soak of 9-11 minutes is performed with the engine turned off. Data for the phases can be seen in Table 9.

	Europe	**USA (EPA & CARB)**
Applicability	Positive-ignition engined vehicles.	Gasoline-, methanol- and gaseous-fuelled vehicles.
Preparation	**Loading of carbon canister** 50/50 Butane/Nitrogen **Fuel drain and fill** Drain and fill to 40±2% of nominal tank volume Fuel temp. 10-26ºC **Preconditioning** Cycle: UDC + 2×EUDC Temp. 20-30ºC **Soak** Temp. 20-30ºC 12-36 hours	**Fuel drain and fill** Drain and fill to 40% of nominal tank volume Fuel temp. 7-16ºC **Soak** Temp. 20-30ºC 6-36 hours **Preconditioning** Cycle: UDDS (FTP72) Temp. 20-30ºC **Fuel drain and fill** Drain and fill to 40% of nominal tank volume Fuel temp. 7-16ºC **Loading of carbon canister** 50/50 Butane/Nitrogen
Exhaust test	**Cold start test (Type I)** NEDC Temp. 20-30ºC **Evaporative system preconditioning drive** UDC Temp. 20-30ºC	**Cold and hot start test** FTP-75 Temp. 20-30ºC **Running loss test** EPA 32-38ºC CARB 38-43ºC
Evaporative emissions test	**Hot soak test** Time 60±0,5 min Temp. 23-31ºC **Soak** Time 6-36 h Temp. 18-22ºC **Diurnal test** Time 24 h Temp. 20-35ºC	**Hot soak test** Time 60±0,5 min Temp. 34-36ºC **Soak** Time 6-36 h Temp. EPA 21-24ºC Temp. CARB 17-20ºC **Diurnal test** Time EPA 48 h Time CARB 72 h Temp. 22-36ºC
Emission limits	**Euro 5:** 24 hour diurnal + hot soak <2.0 g/test	**EPA TIER II:** 48 hour diurnal + hot soak <0.95 g/test **CARB LEV II:** 72 hour diurnal + hot soak <0. 5 g/test

Table 8 Comparison of the main features of the European and US evaporative test procedures. Source: UN/ECE Regulation No 83 Annex 7, CFR 40 Part 86 §133-96 and §138-96

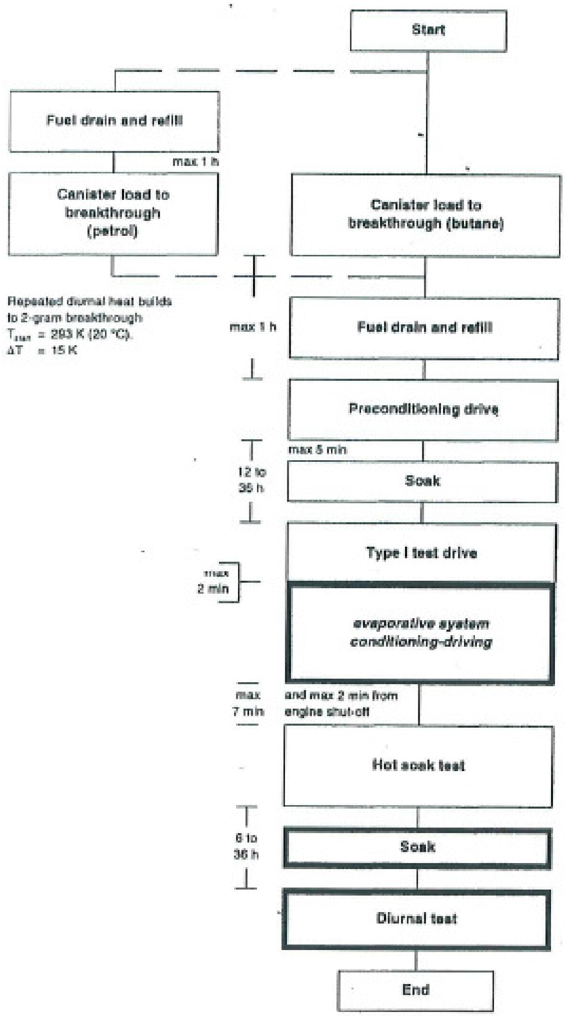


Figure 32 EC evaporative emissions test sequence.

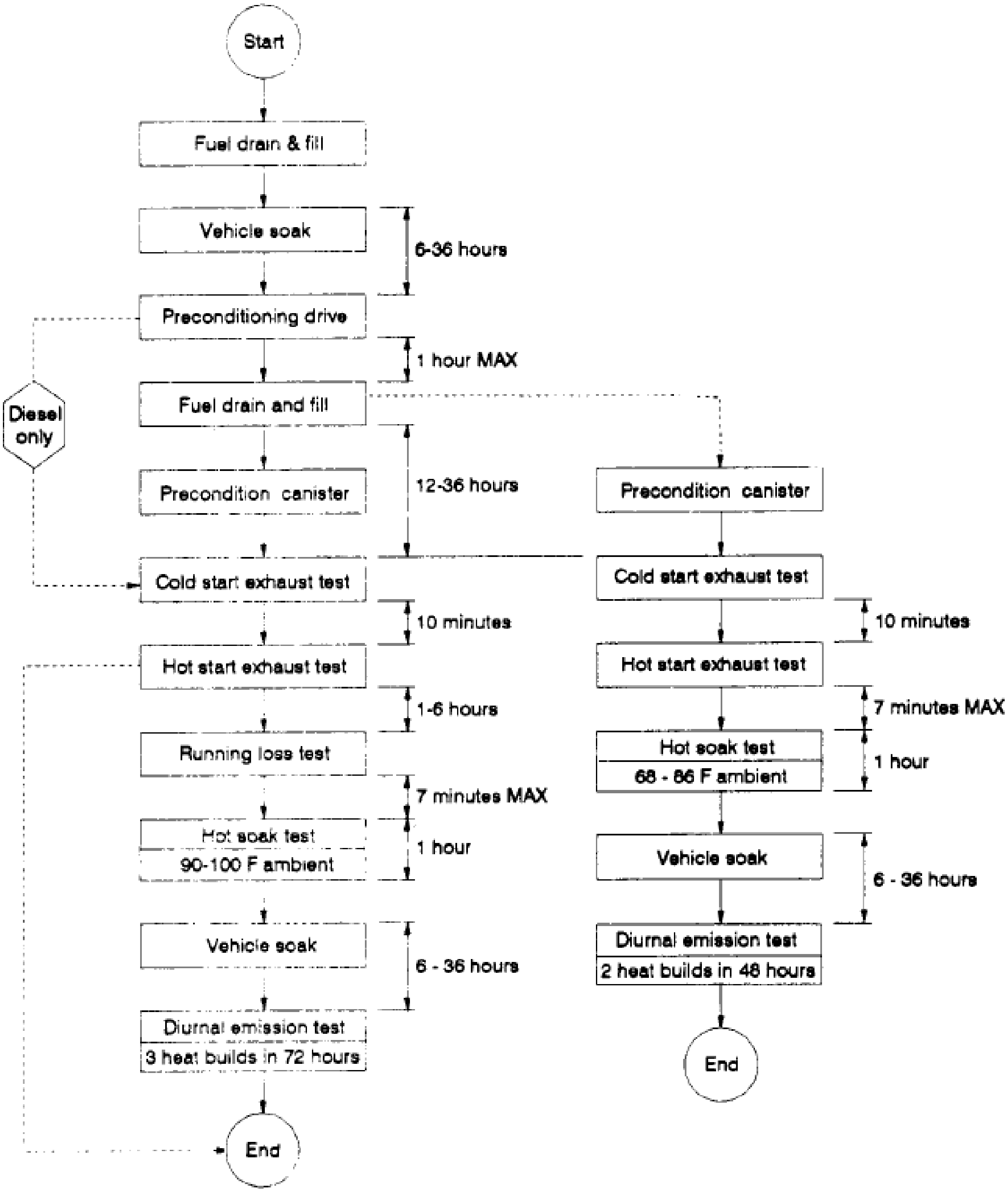


Figure 33 US federal test procedure. Temperatures and times given in this schematic may be different from those stated in the legislative documents.

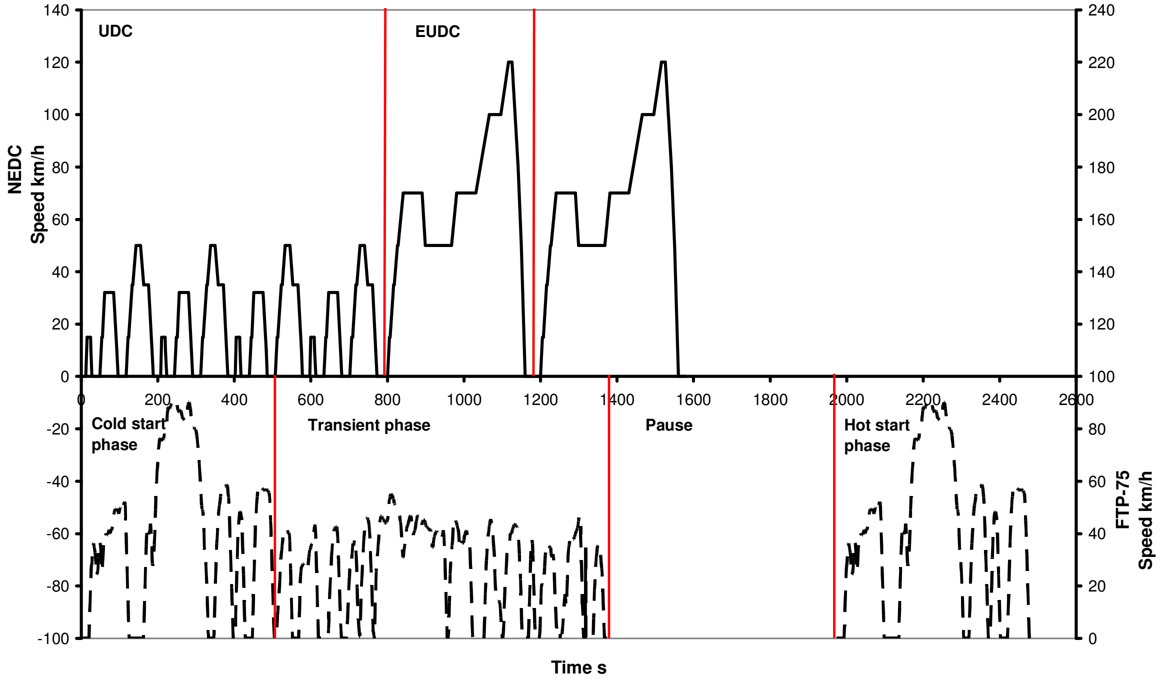


Figure 34 Driving cycles for the European and US test procedure. Source: UN/ECE Regulation No 83 Annex 4, CFR Title 40 Part 86 Appendix I (a)

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	Cold start phase	Transient phase	Hot start phase
Distance [km]	5,8	6,3	5,8
Duration [s]	0-505	505-1369	0-505

Table 9 Length and duration of the US federal driving cycle. Source: CFR Title 40 Part 86 Appendix I (a)

The EC procedure uses different driving cycles. The difference in the preconditioning of the vehicle is that the European procedure implements a notably longer driving cycle in the first preconditioning. Similar to the federal US driving cycles is that an urban driving cycle is used.

The first preconditioning drive consists of one UDC and two EUDC. A diagram showing both cycles can be seen in Figure 34. The par one cycle is composed of four identical parts, repeated without interruption. The total duration of the cycle is 780 s. They are devised to represent city driving conditions and characterized by low speed, low engine load and exhaust gas temperatures. The average speed of the cycle is 18.7 km/h and the maximum 50 km/h.

The EUDC cycles follows immediately and is added to account for more aggressive high speed driving modes. The average speed of this segment is 62.6 km/h and the maximum speed 120 km/h. The total duration of two EUDC cycles is 800 s.

	UDC	EUDC
Distance [km]	1.013	6.955
Duration [s]	195	400

Table 10 Length and duration of the European driving cycle. Source: UN/ECE Regulation No 83 Annex 4

The second preconditioning is also used as an exhaust emission test. However emission sampling is not necessary but the same driving cycle can be used as an evaporative system conditioning drive for the hot soak test.

Different cycle temperatures for the hot soak test are used in the procedures. EPA requires 32.2°C – 37.8°C (90°F - 100°F). CARB requires 37.8°C – 43.3°C (100°F - 110°F). The EC procedure requires 23°C - 31°C. Different temperatures are also required for the stabilization time after the hot soak test. For EPA it is 22.2°C (72 ± 3°F) and for CARB 18.3°C (65 ± 3°F). For the EC the requirement is 22 ± 3°C.

The diurnal tests use a 24 h cycle with heat build up. The same cycle is looped 1-3 times depending on the test. The EC test is only run for 24 h, whereas the US procedure has a running time of respectively 2 and 3 days. However the temperature profile differs between EC and the two US cycles.

	Europe		USA	
RVP	56-60 kPa		60-63 kPa	
Distillation	70ºC	24-40%	IBP	23.9-35ºC
	100ºC	50-58%	10%	49-57ºC
	150ºC	83-89%	50%	93-110ºC
	190-210ºC	100%	90%	149-163ºC
			EP	213ºC
Hydrocarbon analysis				
olefins	max 10%		max 10%	
aromatics	29-35%		max 35%	
benzene	max 1%			
saturates	report		remainder	
Elements				
sulphur	max 10 mg/kg		15-80 mg/kg	
phosphorous	max 1.3 mg/l		max 1.3 mg/l	
lead	max 5mg/l		max 13 mg/l	
Octane	RON 95 MON 85		RON min 93	

Table 11 Fuel specifications for evaporative emissions tests. Source: UN/ECE Regulation No 83 Annex 7§3.2, CFR 40 Title 86§113-04

Yet another important difference is the prescribed fuel specifications. The US procedure allows a slightly higher RVP than do the European counterpart. Oxygen content is limited to 1% by volume in the European procedure while nothing is specified with regards to oxygenates in the US fuel specification. Some characteristics of the test fuels ca be found in Table 11.

4.2.3 Evaporative emissions requirements

The evaporative emissions requirements consist of two measurements. One is a hot soak test that estimates the evaporative losses when a warm vehicle is parked. The other determines the emissions obtained from the vehicles fuel system during a diurnal heat build up that simulates the temperature changes during a day. The total evaporative emission result consists of the HC-mass sum from both the hot soak and diurnal measurements. For the 3- and 2-day tests, the highest diurnal result for each 24 hour period is valid. HC-emissions from a non-operated vehicle are measured with both the hot soak and the Diurnal measurement methods.

	EC, g/test (EU5 >)	3-day Diurnal, g/test (LEV II > (CARB))	2-day Diurnal, g/test (TIER II> (EPA))
Passenger cars, Light duty trucks	2,0	0,5	0,95

Table 12 Evaporative emission requirements.

4.2.4 Test equipment

Common for the three procedures described above is that they are designed to determine hydrocarbon emissions as a consequence of diurnal temperature fluctuation over a given time and hot soak during parking of the vehicle. To measure the diurnal losses preferably an evaporative emission measurement enclosure is used. These enclosures are most often named VT-SHEDs (Variable Temperature Sealed Housing for Evaporative Determination), and are specifically used to quantify the evaporative emissions from a non-operating vehicle in a sealed enclosure over various time periods and at different temperatures. Figure 35 shows a VT-SHED with open door.

The hydrocarbon emissions are measured inside the enclosure by taking an air sample and measuring the mass of hydrocarbons in the air with a given resolution. Alternatively, an on-line measurement can be performed to provide a continuous recording of the hydrocarbon level. In both cases most commonly the hydrocarbon measurement is performed using a hydrocarbon detector of the flame ionization detector type (FID).

Figure 35 AVL VT-SHED

4.3 Vehicle tests

This phase of the work consists of the testing of three current model passenger cars with different hardware solutions for the evaporative emission systems. The purpose was to investigate differences in results between the different system solutions when undergoing evaporative emission testing according to EC and US standards. One vehicle was equipped with an evaporative emission system that fulfills the US requirements except for the ORVR system not installed, one was equipped with a system that usually performs well in the EC test and one vehicle was equipped with a system that most likely will perform poorer in the EC tests, based on earlier testing on aged cars.

4.3.1 Test program overview

The vehicles were tested in as received condition without any modifications. All test objects were of model year 2007 or later and specified for the Swedish market. One objective of the testing was also to investigate the performance of the systems when aged. This is why a requirement for an odometer reading of 35 000-45 000 km was set.

A deviation from set procedures was made in the question of the fuel used in the test. The tests were executed with gasoline 95 octane E10 according to EN228 fuel specification. The intention was to investigate any influence of increased RVP (Reid Vapour Pressure) as a result of low ethanol blending.

Property	**Units**	**Gasoline 95, E10, Batch: 2009033883**	**EN 228**	
Research octane number (RON)		95,2	≥ 95	
Motor octane number (MON)		85,0	≥ 85	
Lead	mg/l	≤ 1,0	≤ 5	
Density @ 15℃	kg/m^3	747,5	720-775	
Sulphur content	mg/kg	≤ 3	≤ 10	
Oxidation stability	minutes	≥ 600	≥ 360	
Existent gum content (solvent washed)	mg/100ml	≤ 4	≤ 5	
Copper strip corrosion (3 h @ 50℃)	rating	1A	class 1	
Appearance		Bright and Clear	Bright and Clear	
Olefins	vol %	3,2	≤ 18,0	
Aromatics	vol %	26,5	≤ 35,0	
Benzene content	vol %	0,52	≤ 1,0	
Oxygen content	mass %	3,48	≤ 3,7	
Oxygenates content -methanol -ethanol -iso-propyl alcohol -iso-butyl alcohol -tert-butyl alcohol -ethers (5 or more C-atoms) -other oxygenates	vol %	0 10,0 0 0 0 0 0	≤ 3 ≤ 10 ≤ 12 ≤ 15 ≤ 15 ≤ 22 ≤ 15	
Vapour Pressure Summer (Sweden) Winter (Sweden)	kPa	61,0	45 - 70 65 - 95	
Distillation curve			Summer	Winter
% evaporated at 70℃, E70	℃	44,3	20 - 48	22 - 50
% evaporated at 100℃, E100	℃	56,9	46 - 71	
% evaporated at 150℃, E150	℃	93,3	≥ 75,0	
IBP	℃	38,9	-	
Temp. at 10% V/V evap.	℃	53,1	-	
Temp. at 50% V/V evap.	℃	84,9	-	
Temp. at 90% V/V evap.	℃	143,4	-	
FBP	℃	185,0	210	

Table 13 Test fuel analysis report

4.3.2 Test objects

No.	Engine size [litres]	Evaporative emission control system
1	2.0	US market specification 61 litre six-layer plastic fuel tank
2	1.4	European market specification 55 litre fuel tank Canister dry mass 210g capacity 40 g
3	1.0	European market specification 42 litre HDPE tank with fluorinated polyethylene inner layer and integrated canister

Table 14 Properties of the tested vehicles.

4.3.3 Test execution

The vehicles were tested in their numbered order. The same test sequence was used for all objects starting with the EC procedure, followed by EPA and finally testing according to the CARB procedure. No interruptions were allowed once a procedure was started. The testing was planned and resourced so that the intermediate times between the steps given by the test procedures were held. These intermediate times are shown exactly in Figure 32 and Figure 33.

Same soak times were applied in the different steps in all the tests. The soaking was also performed in the same area and at constant temperature in all cases. The vehicles were placed indoors at a temperature of 18℃ for 8 hours before the start of the test sequence and fuel fill. No driving or engine starts were done besides what was allowed by the test procedures.

4.3.4 Deviations from the test procedures

No exhaust emission samples were taken during the test sequences. The main objective of the testing was to investigate the performance of the vehicles evaporative emission systems. Therefore it was considered unnecessary.

A deviation was made to the US procedure due to lack of time. A common temperature of 20℃ was decided to the stabilization after the hot soak test, for correct temperatures see Table 8. The test sequence was also looped so that after the hot soak test the test sequence was reversed back to the second fuel fill and canister fill and then continued. The influence of this to the results was considered to be insignificant.

4.3.5 Test site

The tests were performed at the testing laboratories of AVL MTC in Haninge/Stockholm Sweden between 2009-11-30 and 2009-12-31.

4.3.6 Test results

The results of the hot soak test and adherent diurnal test are summarized to a total result. The actual statutory limit values for evaporative emissions can be seen in Table 12 of this report. The results are presented as a difference between the start hydrocarbon value and the value at the end of test. The results are presented in HC mass (g/test). For the 2- and 3-day diurnal measurements, the results are presented for each 24-hour period, where the highest HC-value for a 24-hour period is valid as the result of the test.

Best results was achieved with vehicle 1, despite that it did not pass the CARB requirements.
Neither of vehicles 2 and 3 fulfilled the EPA requirements. This result was expected since none of the cars were equipped with evaporative emissions systems designed for the US market stricter emission requirements. The added strain caused charcoal canister breakthrough to occur during the tests resulting in elevated levels of HC. All vehicles passed the EC requirements.

The testing of vehicle 2 had to be stopped during the diurnal test according to the CARB method after approximately 48 hours due to too high HC values in the VT-SHED chamber. Due to lack of time the test was not continued. The highest measured HC-value before break of test was 4,378 g for one diurnal period, which is 4.6 times higher than the allowed limit of 0,95 g/test. A value for the 72 h measurement point was calculated with the linear extrapolation. The calculated result should not be seen as absolute certain because the point is outside the discrete set of data points, but gives a fair indication of the result. For vehicle 3 the alarm limit of the FID analyser in the VT-SHED was turned off and the test was continued despite high HC concentration. The measurement at 72 h was performed manually.

The results of the measurements are presented in Table 15 and Figure 36.

	Vehicle 1	**Vehicle 2**	**Vehicle 3**
Hot Soak, EC	0,032	0,185	0,135
Diurnal, EC	0,159	1,452	1,100
Evaporative emission, EC [g]	**0,191**	**1,637**	**1,235**
Hot Soak, EPA	0,042	0,311	0,174
Diurnal, EPA	0,623	4,378	8,532
Evaporative emission, EPA [g]	**0,665**	**4,689**	**8,706**
Hot Soak, CARB	0,062	0,405	0,234
Diurnal, CARB	0,740	(8,877)	20,968
Evaporative emission, CARB [g]	**0,802**	**(9,282)**	**21,202**

Table 15 Test results [g/test]

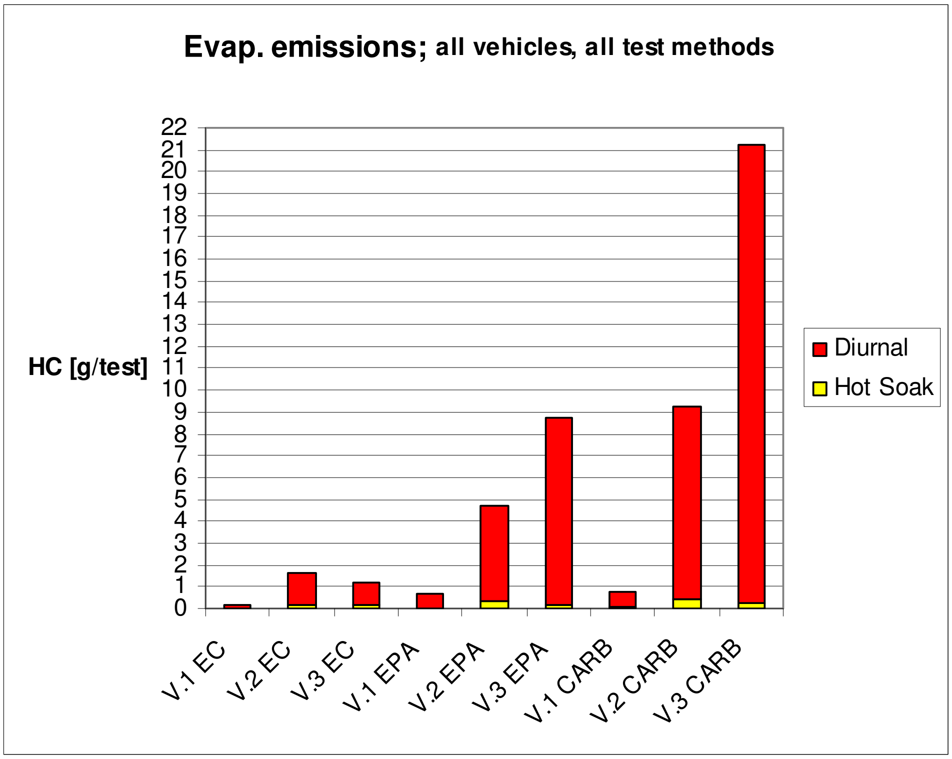


Figure 36 Evaporative emissions for all vehicles

As expected, the results show that the major fraction of the evaporative emissions is generated by the diurnal test. Figure 37-Figure 39 show individual results for the test vehicles and the distribution of the measured HC-levels between the hot soak and the diurnal tests. Note that the vertical scale vary between the figures. Numerical results for each test are presented in Table 15.

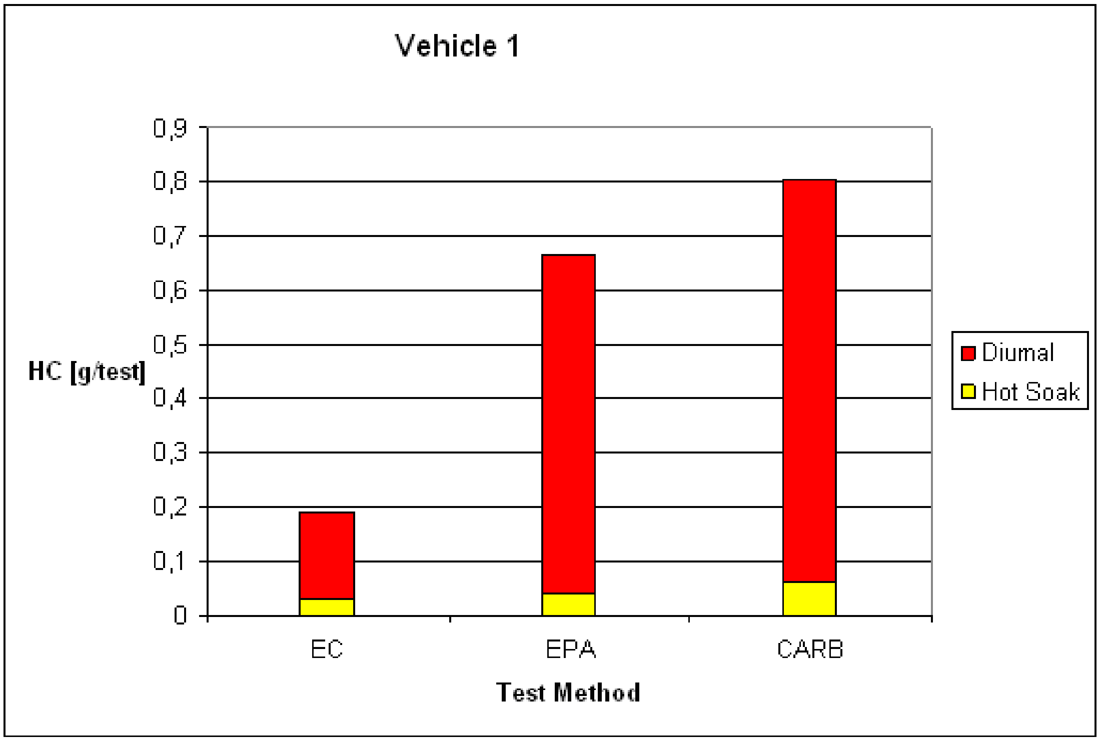


Figure 37 Test results for vehicle 1

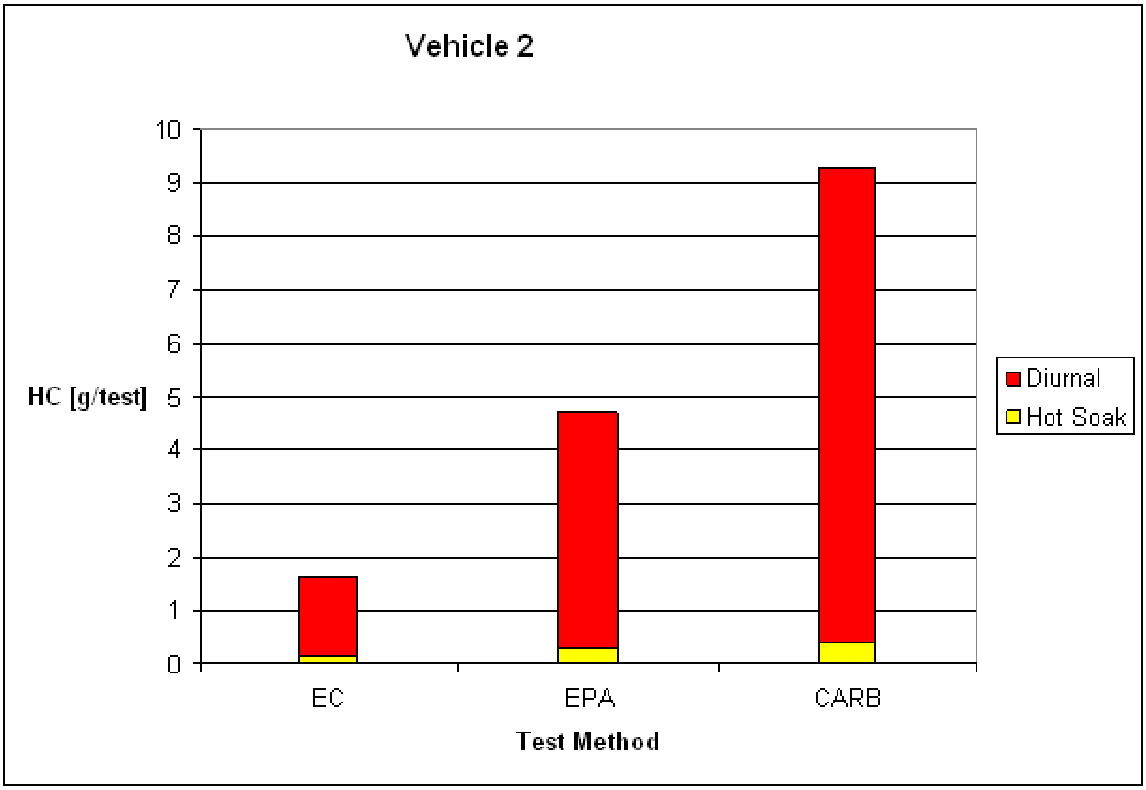


Figure 38 Test results for vehicle 2

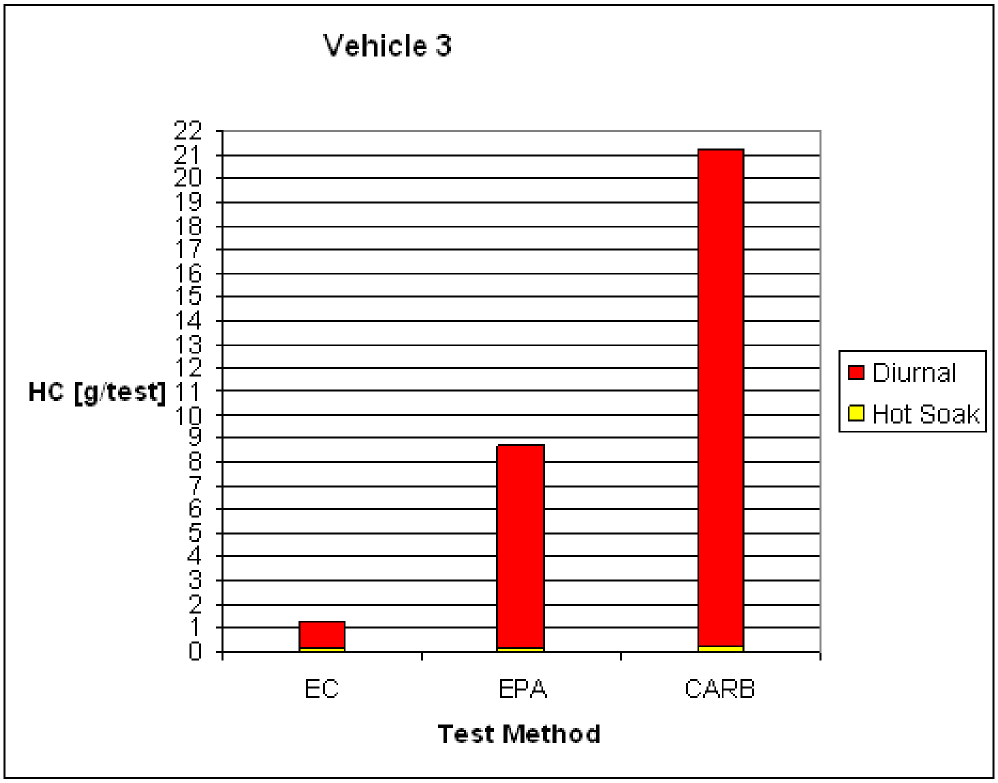


Figure 39 Test results for vehicle 3

In the EPA and CARB tests the highest HC-values are generated in the last 24 hour periods. Vehicle 1, that has an evaporative emission system essentially designed for the US market, has significantly lower HC-values and the growth of the HC mass is modest. For the two vehicles equipped with a system for the European market the growth of the evaporative emissions increases considerably after 24 hours of testing. The second and third temperature cycling have levels far above the set limits. The HC-mass as a function of time in the CARB test can be seen in Figure 40.

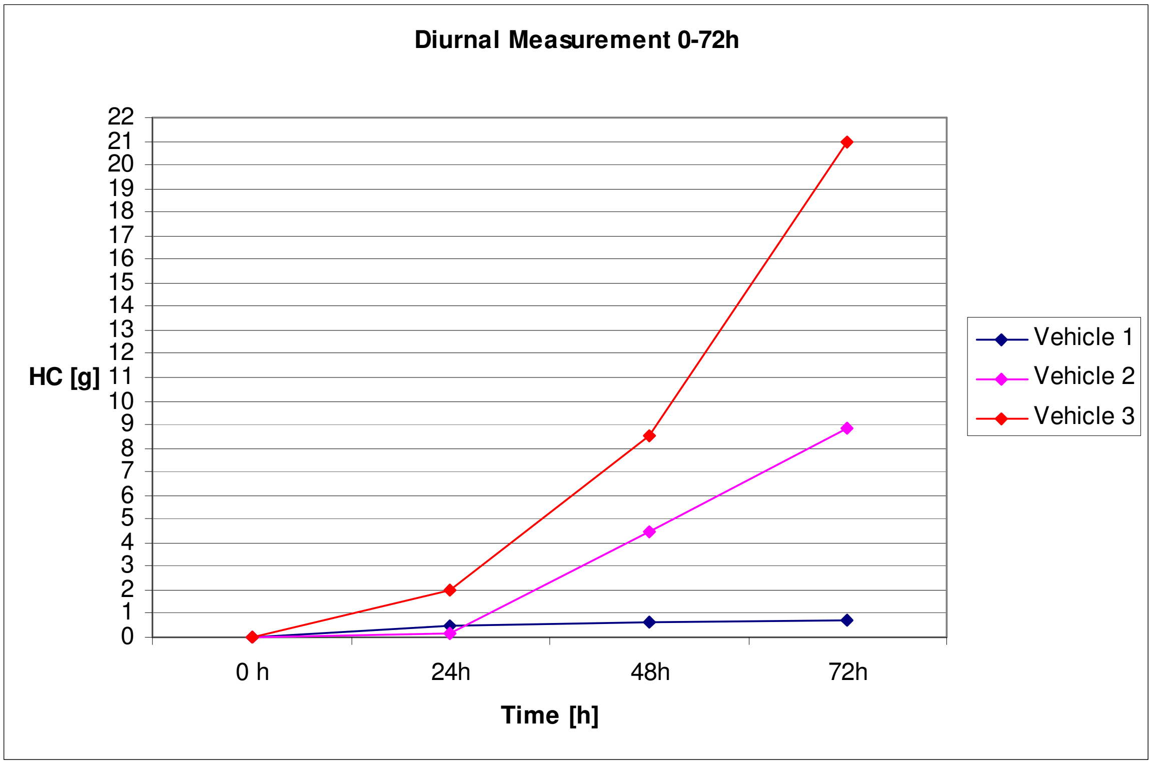


Figure 40 Evaporative emissions, CARB. Note that the data point for vehicle 2 at 72 hours is extrapolated.

4.3.7 Test remarks and conclusions

Only one individual of each vehicle type was tested so the results can not be considered to be statistically confirmed. The results should therefore not be considered as absolute for the vehicle type.

The evaporative emission systems were considered to be functional in all the test vehicles. All the vehicles passed the EC requirement with the E10 fuel.

The physical size of the charcoal canister has an influence to the point of time when canister breakthrough occurs. A larger volume canister makes it possible to adsorb more HC during long term parking and should consequently reduce the vehicles evaporative emissions.

The charcoal canister size and location in the cars varied. The size of the canisters varied with fuel tank volume, decreasing with the volume. Vehicle 1 had the canister placed next to the fuel tank and also had the canister with the largest volume while in vehicle 2 the canister was placed in the vehicles engine compartment closer to the engines inlet manifold. Vehicle 3 had a solution where the charcoal canister was integrated with the fuel pump in one unit and placed inside the fuel tank. Vehicle 3 also had the canister with smallest volume.

4.4 Technology for the prevention of evaporative emissions

4.4.1 Fuel tank technology

Independent of fuel tank technology most fuel loss can be attributed to tank interface openings such as pinch-offs, weldings, hose connections and joints. pumps, filters and even canisters are therefore commonly integrated into the fuel tank so as to minimize the number of possible leaks.

In the last years increasingly stringent legislative demands on low evaporative emissions, fuel tank manufacturers and OEM's are struggling to find the best combination of low permeability, high durability, fuel efficient tank shape, low cost, high security and recyclability. Two main strategies can be discerned; plastic tanks and steel tanks. On balance, plastic appears to have almost eclipsed steel as the material of choice by carmakers in Europe and USA.

Figure 41 Plastic and steel fuel tank installation rates in Europe

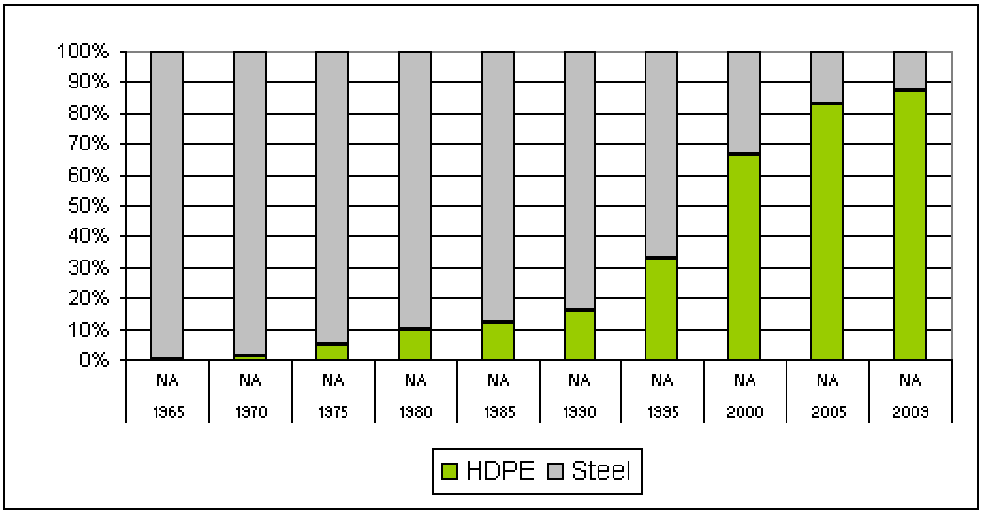


Figure 42 Plastic and steel fuel tank installation rates in USA

Although the use of plastic tanks are dominant in Europe and North America, Japan still favours the steel tanks mainly for its lower cost. 2006 Just-Auto estimates that installation rates of plastic tanks in Japan are at 26% with potential to reach 31% by 2012.

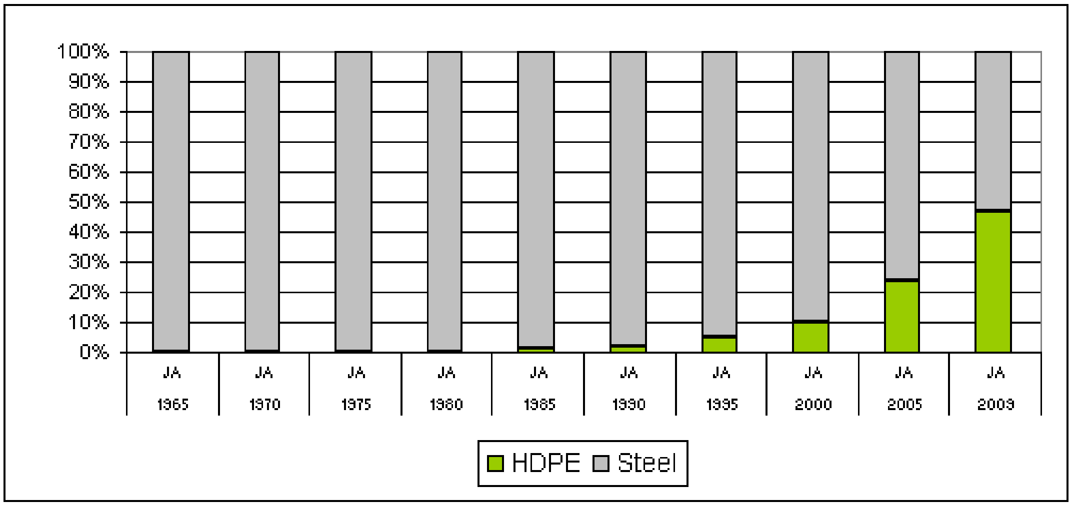


Figure 43 Plastic and steel fuel tank installation rates in Japan

Still, there might be a niche for steel tanks in North America where Corus report having discussions with OEM's regarding steel tanks for biodiesel fuel. The materials currently used for these tanks are reported to manifest performance problems with biodiesel fuels, especially when water is present in the fuel.

Plastic tanks

Plastic fuel tanks are either blow molded or thermoformed. The plastic most commonly used in fuel tanks is high density polyethylene, HDPE, a material notorious for its low permeability resistance. To address this problem a seal has to be applied to the plastic tank. This is most commonly achieved though one of three main strategies

Multi-layer plastic tanks dominate the US market since they yield the highest permeability resistance. The material is a composite of usually six layers stacked as described in Figure 44. The composite layers have different purposes where the inner and outer HDPE layers provide durability and strength while the inner polymer layer, usually EVOH, provide excellent sealing properties.

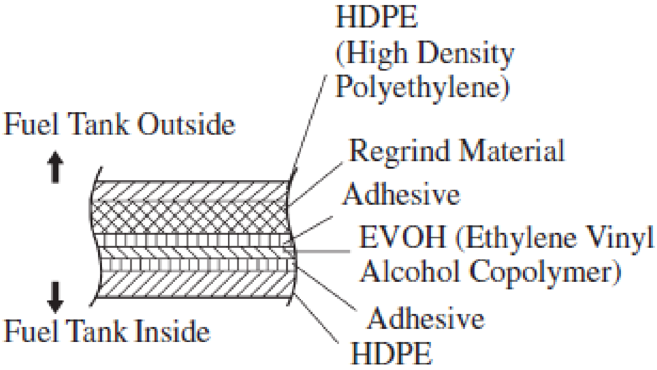


Figure 44 Six-layer composite plastic fuel tank wall. Source: Toyota

The main drawback of the composite material is its high production cost. On markets outside US, with less strict evaporative emission legislation this technique is yields to other less expensive manufacturing methods.

Barrier layer plastic tanks are the most commonly used on the European market. A high permeation resistance barrier layer is applied to the inside of the HDPE tank in order to provide the sealing property that HDPD lacks. Barrier layers are produced by a variety of techniques such as sulfuration, fluorination (teflon coating) and co-extrusion. Concerns have been raised as to the durability of inner barrier layers and the risk that they scratch and wear out with time, see **Error! Reference source not found.**.

Selar tanks are mainly used on small, lightweight vehicles such as garden equipment, motorcycles and ATVs. Selar® RB is a compounded resin developed by DuPont. When added to the polymer during the blow molding process it improves the permeability resistance of the product.

Steel tanks

A few decades ago most fuel tanks were made of steel. Steel has a high resistance to permeation but a safety concern is that steel tanks can explode when exposed to fire. Steel tanks are also considered less recyclable.
To resist corrosion the steel has been plated on the inside with terene (lead-tin) or galvanized (zinc-nickel or zink-iron). As of 2005 lead is not used in fuel tanks for environmental reasons and corrosion has become a challenge for fuel tank manufacturers.

Stainless steel tanks have been tested but the manufacturing is more expensive and the material is prone to cracking.

In may 2003 Corus Automotive announced that they won a contract to supply Ford with its advanced Neotec steel tank and will supply the new material for fuel tanks required for the Ka and StreetKa models. Since then Proton and MG Rover also chose Neotec tanks for their 2005 models. Neotec is a hot-dip tin-zinc alloy coated steel available in sheet or coil. Its properties allow it to be formed into complex shapes using conventional stamping and welding processes. In fact Rover reports not having to change their press lines or welding equipment for the new Neotec material.

Bladder tanks

When introducing the Toyota Hybrid System on the North American market high demands on drastic reduction of gasoline vapour were set. In order to meet this, a fuel tank system called Vapour Reducing Fuel Tank System was developed. It is essentially a combination of a variable volume plastic fuel tank inside a permeation resistant steel tank. The inner bladder is made from a six-layer permeation resistant plastic composite and will shrink or expand in proportion to the remaining fuel in order to reduce the amount of fuel vapour. The outer tank is a double enclosed structure that ensures reliability and safety.

Furthermore a mechanical seal is incorporated in the system to seal off the tank from the canister at all times except when refuelling. That way the canister can be purged less frequently improving the precise air-fuel ratio control. A detailed outline of the Toyota bladder tank is shown in Figure 45.

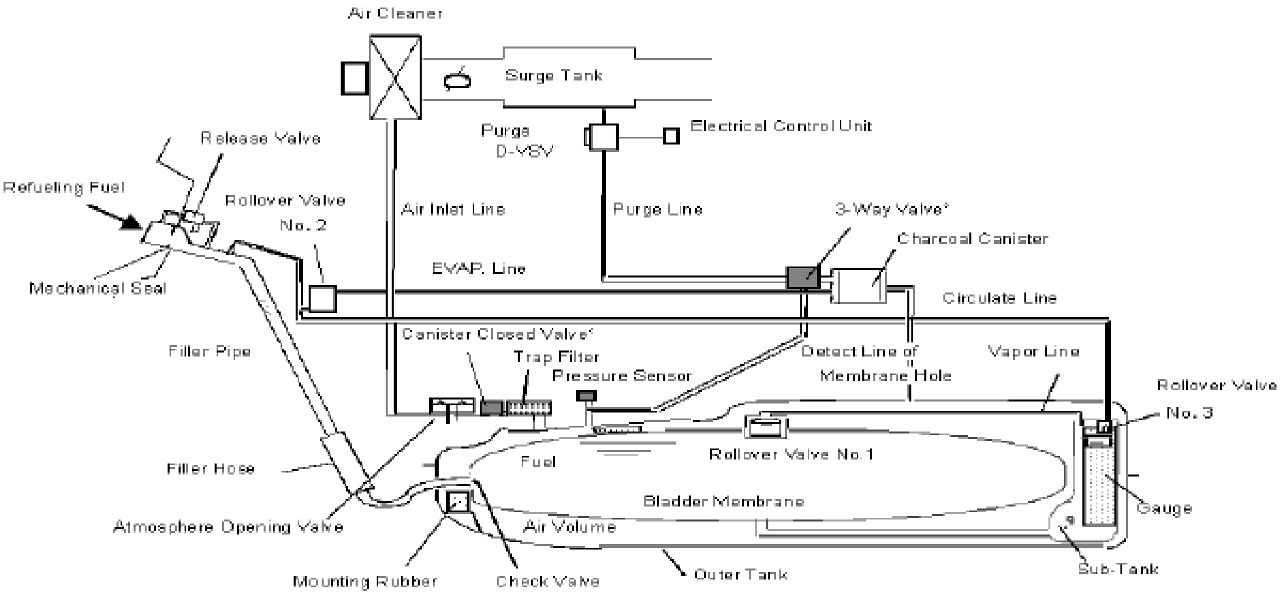


Figure 45 Outline of Toyotas bladder tank

4.4.2 Carbon canisters

Carbon canisters are used in fuel systems to adsorb fuel vapour from the fuel tank and prevent it from escaping into the atmosphere. The adsorption agent is usually activated carbon, either as polymeric foam, pellets, granules or as part of an extruded ceramic. Although larger molecules are present in fuel vapours the primary constituents are C4-C6 i.e. buthane, penthane, hexane and similar molecules. Figure 46 show a comparison between fuel composition and captured vapour composition.

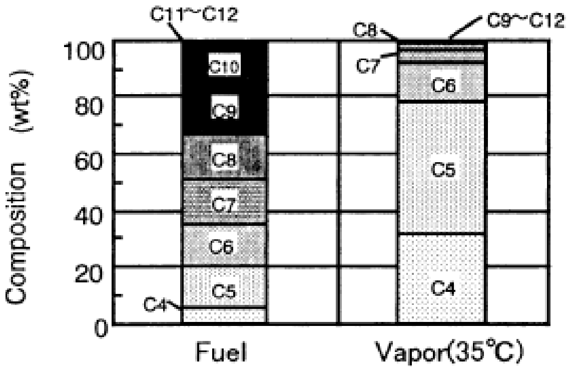


Figure 46 Molecular distribution in fuel and fuel vapour at 35 ºC.

One important measure of a canister's efficiency is the working capacity. It is defined as the difference in mass between a fully loaded and a purged canister. It has been found that carbon canister working capacity can eventually deteriorate with the number of adsorption/purge cycles. It is believed that this is a result of high boiling fuel components filling up the micropores of the activated carbon leaving less room for adsorption. Figure 47 describes the aging process of a carbon canister. In the first cycle approximately one third of the working capacity is lost. The working capacity continues to decrease but after the tenth cycle this trend levels out and a period of stable working capacity begins. After a long stable period the working capacity starts to decrease again. This is called the deterioration phase and marks the end of the canister's useful life.

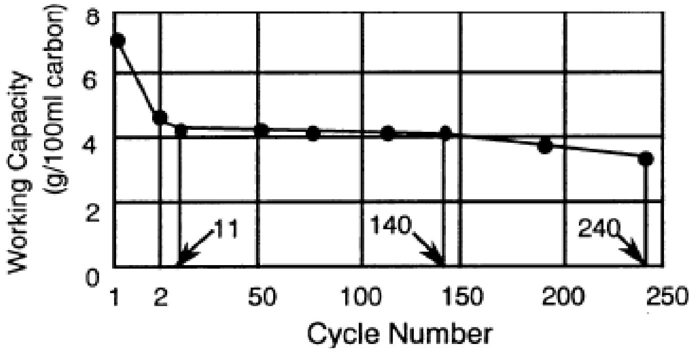


Figure 47 Carbon canister aging

During this first aging phase the number of micropores larger than 1.3 nm has been found to decrease and the residual hydrocarbon is dominated by smaller molecules, C4-C6. In the stable phase these smaller hydrocarbon molecules are slowly exchanged for larger, high boiling molecules, C7 and over. Meanwhile the number of micropores between 0.9 and 1.1 nm begin to decrease. In the deterioration phase, micropores of the size equivalent to the fuel hydrocarbon molecules decrease.

4.4.3 Hoses

The evaporative emissions from hoses are considered to originate from three sources; emission through the wall, E_W, emission from the hose ends, E_E and emission from fuel leak, E_L so that

$$E_T = E_W + E_E + E_L$$

is the total evaporative emissions from the hose. In Table 16 below the evaporative emissions test results in mg of fuel per day and mm of hose length from two fuel hoses are shown. The tests were conducted at 40ºC constant temperature over six hours. Simulations suggest that slightly more than 50 % of the emission from Hose 1 originated from the ends while emissions from Hose 2 came almost entirely through the wall. No leaks were present in this test.

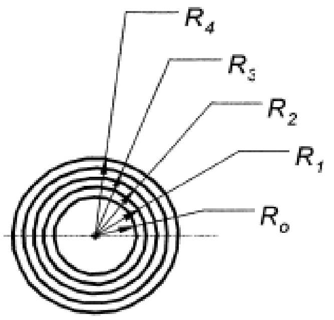
						
	Hose 1			**Hose 2**		
Layer 1 material	NBR			FKM		
Layer 2 material	"New FP"			"New FP"		
Layer 3 material	NBR			ECO		
Layer 4 material	CSM					
Diameter mm	11.9	12.7	13.7	24.6	27.9	36.3
E_T mg/day/mm	0.10	0.10	0.09	0.05	0.05	0.04

Table 16 Evaporative emissions from two hoses constructed from different materials. NBR nitrile rubber, CSM chlorosulfonated polyethylene elastomer, ECO epichlorohydrin rubber, "New FP" unknown

The ever stricter regulatory requirements have made it more and more challenging for vehicle fuel system manufacturers. In addition to low fuel permeability the hoses have to meet oil resistance, crash worthiness, durability and ease of assembly requirements.

The development has moved from nitrile rubber which is extremely permeable to gasoline vapours towards multilayer hoses.

One such concept is the barrier laminate fuel hose F200 developed by DuPont and described in Figure 48. This is a flexible low permeation hose claimed by DuPont to meet CARB LEV II and PZEV fuel permeation compliance. The inner FKM tube and the FEP layer is said to each provide at least two orders of magnitude improvement in permeation resistance relative to NBR. A AEM tie layer ties the barrier to the aramid fiber reinforcement and the AEM cover provides mechanical protection.

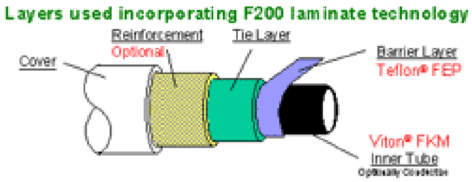


Figure 48 Schematic of DuPont F200 fuel hose. Source: DuPont

An alternative high barrier construction utilizes only an inner veneer of the flouropolymer EFTE as sketched in Figure 49. This thermoplastic has approximately 15 times higher permeation resistance than FKM. Options for cover materials are Nylon or AEM. Since the veneer is rigid coupling may be a problem.

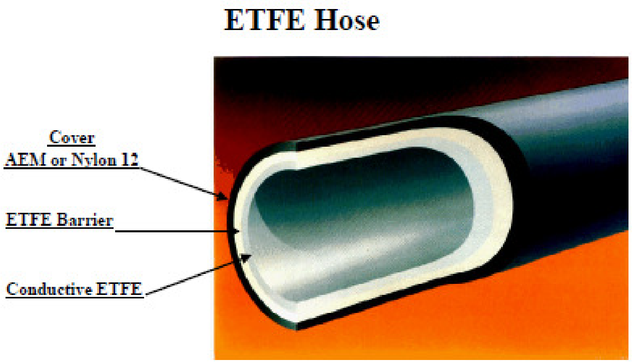


Figure 49 Thermoplastic veneer hose.

4.5 In-service compliance

In addition to the certification tests European emission legislation also require in-service compliance tests up to five yeas of age or 100 000 km which ever is the sooner. This is to ensure the durability of the emission control components. A minimum of three cars are tested against the same requirements as for new cars.

In in-service compliance tests performed at AVL MTC approximately one third of the tested vehicles failed the diurnal + hot soak test, see Figure 50. In parallel tests by TÜV in Germany only a failure rate of one tenth was found. This has been attributed to the ethanol contents in Swedish gasoline.

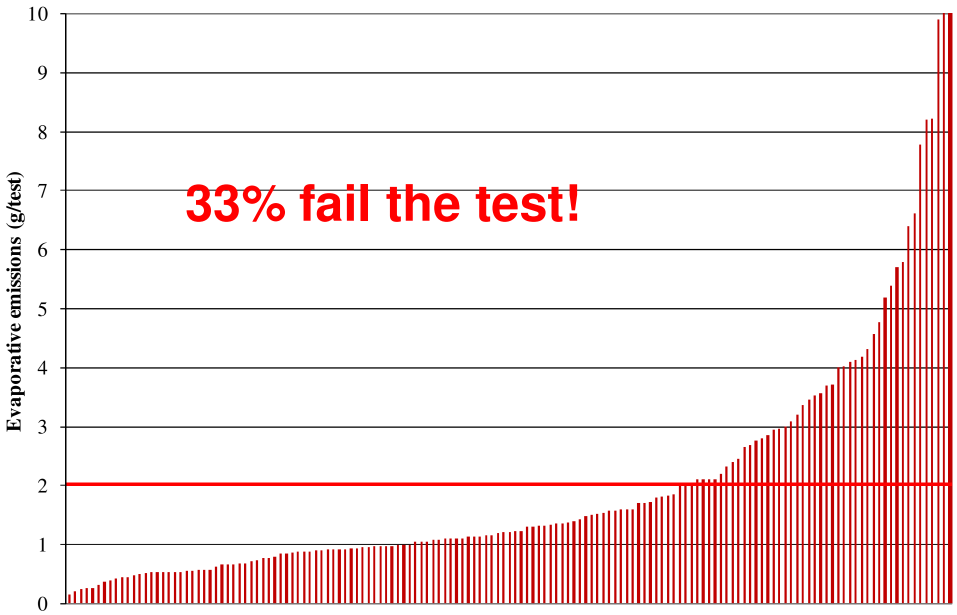


Figure 50 Diurnal + hot soak test results from Swedish in-service compliance tests with Euro III and IV cars (tested 2003-2009).

4.6 Durability

Contrary to the European counterpart, US emission legislation [11] §1824-08 require vehicle manufacturers to demonstrate the durability of the evaporative emission control system and its components throughout the vehicles useful life. The manufacturer is responsible for developing a service accumulation method according to good engineering judgement. The service accumulation method can be based upon whole-vehicle mileage accumulation, bench ageing of individual components or a combination of these approaches.

The fuel used must contain at least the highest concentration of ethanol permissible under federal law.

4.6.1 Whole vehicle evaporative durability demonstration

Mileage accumulation must be conducted for either the entire useful life mileage period or 75% in which case a deterioration factor is calculated. Evaporative emissions test must be carried out at each of five different mileage points including 5000 miles.

4.6.2 Bench ageing evaporative durability procedures

Bench test may be based on an evaluation of

- cycling of canister loading due to diurnal and refuelling events

- use of various commercially available fuels
- vibration of components
- deterioration of hoses etc. due to environmental conditions
- deterioration of fuel caps due to wear

A few examples of approved durability tests will follow.

Pressure cycling
The pressure cycling test is designed to determine the tanks resistance to fatigue due to repeated pressurization The tank is pressurized to within the system normal high pressure and then evacuated to the system normal low pressure. This procedure is repeated for typically 3000-10 000 cycles at a rate of 60 seconds per cycle.
and is performed prior to any preconditioning of the fuel tank.

Slosh test
This test evaluates the tank barrier layer resistance to fuel slosh. The tank is filled to 50% with fuel, sealed and placed on an orbital shaker table set to approximately 2 cycles per second. The may be performed during the preconditioning period.

Permeation tests are run prior and post these tests and any deterioration is recorded.

Canister thermal cycling and vibration exposure
The carbon canister is subjected to thermal cycling followed by vibration exposure. It shall remain functional after the test.

Actuation test
In this test the functional durability of moving components is evaluated. Control valves, cables, linkages are actuated for a minimum number of cycles.

In an effort to determine the possible abrasive effects of fuel slosh the Engineering and certification branch monitoring and laboratory division of CARB performed an experiment on six small HDPE tanks in 2002, [47]. The tanks were identical and selected on their uniform geometry. The tanks were send for barrier treatment, three tanks were flourinated and the remaining three were sulfonated. The treated tanks were filled with MTBE containing gasoline fuel and soaked for a minimum of four weeks. After soaking the tanks were emptied, dried and immediately refilled to 50% capacity with California CERT fuel. Each tank was then pre-weighed, sealed and placed in a SHED where subjected to multiple consecutive 24 hour diurnal temperature profiles. The tanks were post weighed after each 24 hour cycle and the weight loss determined until the deviation in the daily weight loss was below 0.04 g. An orbital shaker table set to two cycles per second was then used to subject the tanks to 1.2 million slosh cycles over seven days. This treatment was followed by another term of multiple diurnal temperature cycles and daily weightings. The average stabilized weight loss of each tank per square meter of tank inner surface and day before and after sloshing is presented in Figure 51. These numbers can be compared with the 10.4 g/m^2/day permeation rate of the untreated tank. Though the data at hand is too small to compare the permeation resistance performance of the two barrier layer approaches it seems clear that both improve permeation resistance vastly and that the sloshing durability of sulfonation exceeds that of fluorination.

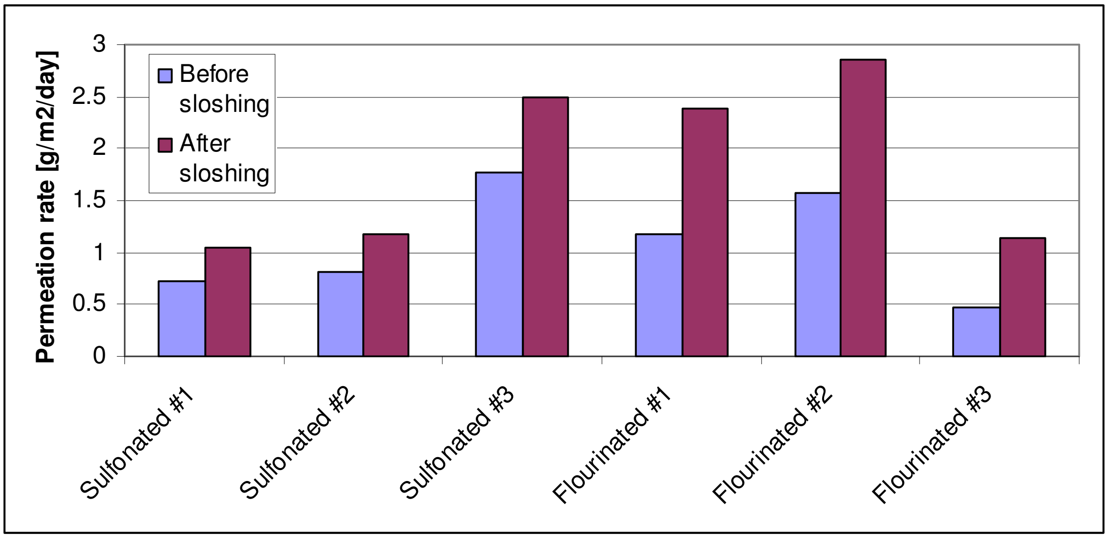


Figure 51 The effect of 1.2 million sloshing cycles on fuel permeation rate.

5 ETHANOL

Sweden has a growing fleet so called environmentally friendly vehicles, see Figure 52. There are two categories environmentally friendly vehicles; alternative fuel vehicles (flex-fuel, bi-fuel and electrical vehicles) that should run mainly on alternative fuel and fossil fuel vehicles with carbon dioxide emissions not exceeding 120g/km. Since the market for alternative fuels is growing the incentive to test flex-fuel and bi-fuel vehicles on both fossil and bio-fuel is rising.

Meaningful tests with alternative fuels will demand a different view on pollutant emissions and modified test procedures. It might be necessary to add further emission components to the list of regulated emissions and some definitions might have to be adjusted to better mirror the true environmental impact of each new car or engine model.

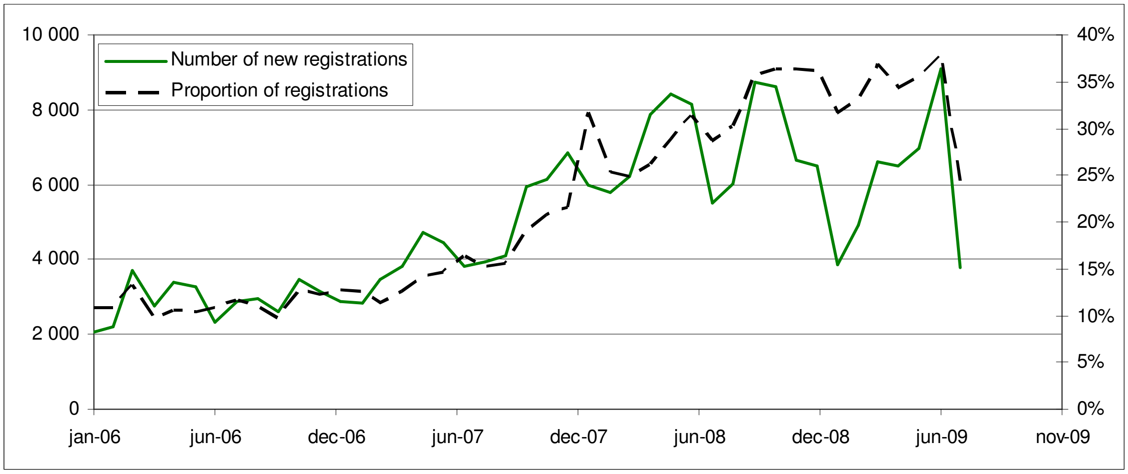


Figure 52 Number and proportion of newly registered environmentally friendly cars in Sweden September 2005-July 2009. Source: The Swedish Road Administration

5.1 Ethanol - E85

The interest of using alcohols, and especially ethanol, as vehicle fuel is high in Sweden. The advantages are many, such as; being renewable, the ethanol can be produced within the country and it is easily mixed with gasoline. Alcohol fuels are considered to be a substantial part of the alternative fuel market, especially in Brazil, USA and Sweden.
With the growing interest it is of most importance to investigate the emission performance of vehicles fuelled with alcohols. The focus in this part is on measurement and calculation of hydrocarbon, alcohol and aldehyde emissions.

The emission regulations in different countries have different ways to treat alcohol fuelled vehicles. Since alcohol fuelled vehicles are more common in USA and Brazil, it is interesting to study their regulations concerning these types of vehicles. A short summary of the regulations in USA and Brazil is therefore included in this study.
When alcohols are used as blending components in gasoline, uncombusted alcohols from the fuel are emitted in the exhaust in various amounts. If a FID (Flame Ionization Detector) is used to measure hydrocarbons, the uncombusted alcohol will be included in the measurement. In the EU regulations hydrocarbons are measured with FID, and alcohols and aldehydes are not measured separately. In the US regulations, the alcohol content is measured separately, and the FID measurement is adjusted for the alcohol part. In Brazil the vehicle manufacturer has the possibility to choose between these two methods.

5.1.1 Emission regulations

EU

In the certification process of the Euro 4 regulations, alcohol fuelled FFVs were not tested with the alternative fuel. The tests were performed using petrol only, and there were no differences in the evaluation of the emissions. In Euro 5, applicable from September 2009, this has been changed. The FFVs are to be tested with both fuels according to the Type 1 test in the regulations. The Type 1 test is defined as "Verifying average exhaust emissions at ambient conditions", where the vehicle is tested according to the NEDC test cycle at ambient temperature. From 2011, Type 6 testing at low ambient temperature will be introduced. The test requirements for FFVs are presented in Table 18.

		Limit values - vehicle category M and N_1 class 1													
		CO		**THC**		**NMHC**		**NO_X**		**THC + NO_X**		**PM** (1)		**Particle number** (2)	
		mg/km		mg/km		mg/km		mg/km		mg/km		mg/km		mg/km	
		PI	CI	PI	CI	PI	CI	PI	CI	PI	CI	PI (3)	CI	PI	CI
Euro 4	*2005.01*	1000	500	100	-	-	-	80	250	-	300	-	25	-	-
Euro 5	*2009.09*[4]	1000	500	100	-	68	-	60	180	-	230	5,0/4,5	5,0/4,5	-	$6{,}0 \times 10^{11}$
Euro 6	*2014.09*	1000	500	100	-	68	-	60	80	-	170	5,0/4,5	5,0/4,5	-	$6{,}0 \times 10^{11}$

PI = Positive Ignition, CI = Compression Ignition

(1) A revised measurement procedure shall be introduced before the application of the 4,5 mg/km limit value.
(2) Euro 5: A new measurement procedure shall be introduced before the application of the limit value.
Euro 6: A number standard is to be defined for this stage for positive ignition vehicles.
(3) Positive ignition particulate mass standards shall apply only to vehicles with direct injection engines.
(4) 2011.01 for all models.

Table 17 Emission standards - EU

In EU regulations total emissions of hydrocarbons and non-methane hydrocarbons are regulated. The mandated measurement procedure is by using a FID-instrument, calibrated with propane in synthetic air. Flexible fuelled vehicles are tested according to the same procedure as gasoline fuelled vehicles.

Vehicle category	***Vehicles with positive ignition engines including hybrids***
Reference fuel	***Flex fuel*** Petrol (E5) Ethanol (E85)
Test type	
Gaseous pollutants (Type 1 test)	Yes (both fuels)
Particulates (Type 1 test)	Yes (direct injection) (both fuels)
Idle emissions (Type 2 test)	Yes (both fuels)
Crankcase emissions (Type 3 test)	Yes (petrol)
Evaporative emissions (Type 4 test)	Yes (petrol)
Durability (Type 5 test)	Yes (petrol)
Low temperature emissions (Type 6 test)	Yes(2) (both fuels)
In-service conformity	Yes (both fuels)
CO_2 emissions and fuel consumption	Yes (both fuels)

(2) Test on petrol only for vehicles type-approved before 1 September 2011 for new types of vehicles and from 1 January 2013 for all new vehicles sold. The test will be performed with both fuels on or after these dates.

Table 18 Test requirements for type-approval and extensions (according to European Commission Regulation (EC) No 692/2008 Euro 5 and Euro 6)

Test temperature 266 K (-7 degC)			
Vehicle Category	Class	Mass of carbon monoxide (CO) g/km	Mass of hydrocarbon (HC) g/km
M	-	15	1,8

Table 19 Limits for Type 6 test

There is also a change in the evaluation/calculation of the hydrocarbon emissions from the different fuels. The density used for calculating the mass emissions of hydrocarbons are higher for E85 due to the difference in molecular weight, which leads to an increase of approximately 50%. The effect of this is illustrated in Figure 53.

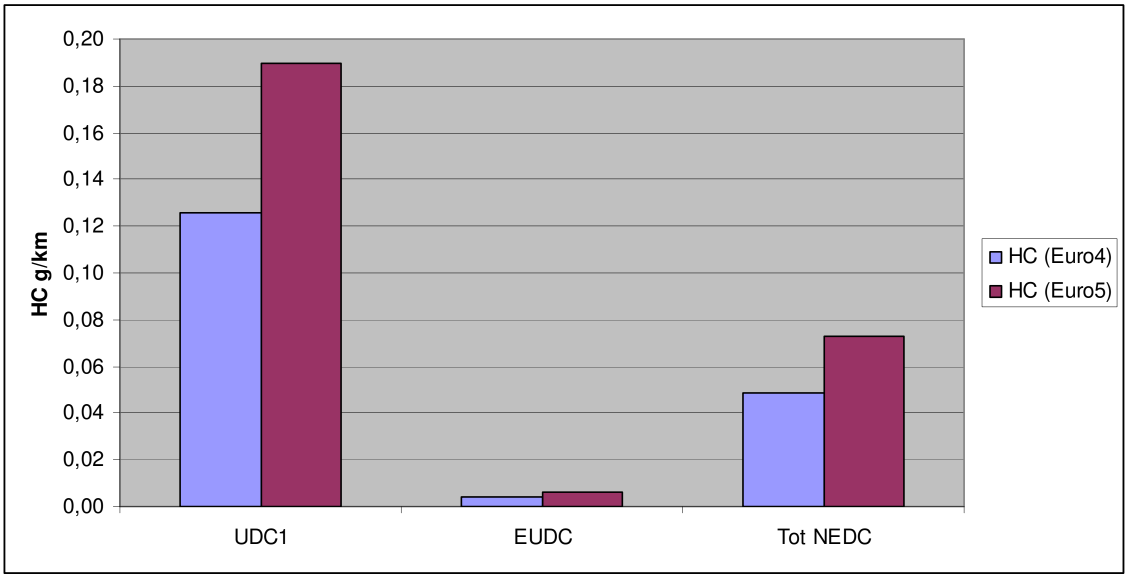


Figure 53 Comparison of THC emissions calculated according to Euro4 and Euro5.

For calculations of mass emission of hydrocarbons, the following densities are used:

Euro 4:
For petrol ($C_1H_{1,85}$) d = 0,619 g/dm^3

Euro 5:
For petrol ($C_1H_{1,89}O_{0,016}$) d = 0,631 g/dm^3
For ethanol (E85) ($C_1H_{2,74}O_{0,385}$) d = 0,932 g/dm^3

For the Euro 5 type approval of a flex fuel ethanol vehicle, the vehicle manufacturer shall describe the capability of the vehicle to adapt to any mixture of petrol and ethanol fuel (up to an 85% ethanol blend) that may occur across the market.

For flex fuel vehicles, the transition from one reference fuel to another between the tests shall take place without manual adjustment of the engine settings.

Brazil

Brazil has an extensive production of ethanol, and ethanol fuelled vehicles is commonly used. All gasoline sold is blended with 20-25% ethanol, and almost nine of every ten new cars sold in the Brazilian market are Flex Fuelled Vehicles.

NMHC is regulated, calculated as:

$NMHC = THC - CH_4$

The density for THC is 576,8 g/m^3, regardless of fuel type.

The vehicle manufacturer has however the right to measure the unburned ethanol and discount this value from the NMHC emissions. In this case the calculations are similar to the US EPA, which will be described below. The ethanol is sampled with impingers and the distilled water from the impingers is analyzed with Gas Chromatography (GC). A response factor for the ethanol is measured by using gas bottles with known concentration of ethanol.

USA

The federal emission standards (set up by US EPA) must be met by all new vehicles sold in the US. California has however been granted, by the Clean Air Act, to adopt its own emission standards which are stricter than the federal standards. These standards are set up by the Californian Air Resource Board (CARB). Some other states have followed and adopted the Californian standards.

The US emission standards are fuel neutral, meaning the same emission limits are applied regardless of the fuel. The standards are also applicable to all vehicle weight categories.

The emission standards are structured into different bins, where the vehicle manufacturer can choose to certify the vehicles to fit into any of the available bins. The vehicle manufacturer have to demonstrate a fleet average for NO_X (according to US EPA) or NMOG (according to CARB, for definition of NMOG please see below).

Besides the emission requirements are based on tests performed using the FTP75 driving cycle, there are supplemental exhaust emission standards that needs to be fulfilled in the certification process. Here the US06 and SC03 driving cycles are used. The supplemental exhaust emission standards must however not be fulfilled for alternatively fuelled LDV/LDTs or flexible fuelled LDV/LDTs when operated on a fuel other than gasoline or diesel. The supplemental exhaust emissions standards are not presented in this part of the report.

The EPA regulations for alcohol fuelled vehicles are based on methanol fuel, whereas CARB has regulations for both methanol and ethanol fuel.

The hydrocarbon, alcohol and aldehyde emissions are included in NMOG (NonMethane Organic Gases), which is regulated. The definition of NMOG is the emissions of NonMethane Hydrocarbons (NMHC) and oxygenated hydrocarbons. The weighted mass (wm) emissions of NMOG shall be calculated as follows:

$$\mathbf{NMOG_{wm} = \Sigma NMHC_{wm} + \Sigma ROH_{wm} + \Sigma RHO_{wm}}$$

ROH are the alcohol content in the exhaust emissions. This is sampled by the impinger method. The sample is thereafter analysed by Gas Chromatography. CARB has also approved PhotoAcoustic Sensor for alcohol measurement.
RHO are the aldehyde (and ketone) content in the exhaust emissions. They are sampled in DNPH-cartridges. The cartridges are thereafter analysed by HPLC.

To calculate the NMOG emissions, the first step is to correct the FID measurements for the presence of methane and oxygenated hydrocarbons:

$$NMHC = {}_{FID}THC – (r_{CH4} \times CH_4) – (r_{C2H5OH} \times 2 \times C_2H_5OH)$$

${}_{FID}THC$ is the THC measured by FID in ppm C.

r_{CH4}, r_{C2H5OH} are the FID response factor for CH_4 and C_2H_5OH respectively. The response factors are determined by the use of gas bottles with known concentration (within ±2% of the specified concentration).

The pollutant concentration is presented in ppm C, hence the factor 2 for ethanol.

The following densities are used in the calculations:
NMHC: 0,577 g/dm^3 (16,33 g/ft^3)
C_2H_5OH: 1,915 g/dm^3 (54,23 g/ft^3)
CH_3CHO: 1,831 g/dm^3 (51,85 g/ft^3)
HCHO: 1,248 g/dm^3 (35,34 g/ft^3)
CH_4: 0,667 g/dm^3 (18,88 g/ft^3)

The FID instrument response is calibrated for HC-only gas – typically propane. Because its response is different for oxygenated hydrocarbons and methane, its output is corrected to account for the presence of these compounds in the measured exhaust. Measured response factors are determined for each compound known to be present and known to affect FID response.

The US EPA recommends the FID to be heated to 113 ºC for methanol fuelled vehicles (instead of 190 ºC which is used for gasoline and diesel fuelled vehicles). The difference in FID sensitivity is illustrated in a separate part – “FID response to Ethanol”.

5.1.2 Vehicle tests

A Skoda Octavia FFV, certified to the Euro 4 emission standard, was used in the testing. The road load curve for the vehicle was kindly supplied by the vehicle manufacturer.

Make	Skoda
Model	Octavia 1,6
Model year	2008
Emission standard	Euro 4
Odometer (km)	9903
Inertia mass (kg)	1350
Displacement (cm3)	1595
Power (kW)	75
Gearbox	M5
Fuel	Gasoline / E85

Table 20 Vehicle specification

Tests were performed at the two ambient temperatures that is used for certification for gasoline from 2009, and for E85 from 2011 – 22 °C and -7 °C.

For the 22 °C tests E85 fuel was used, for -7 °C tests E75 fuel was used.

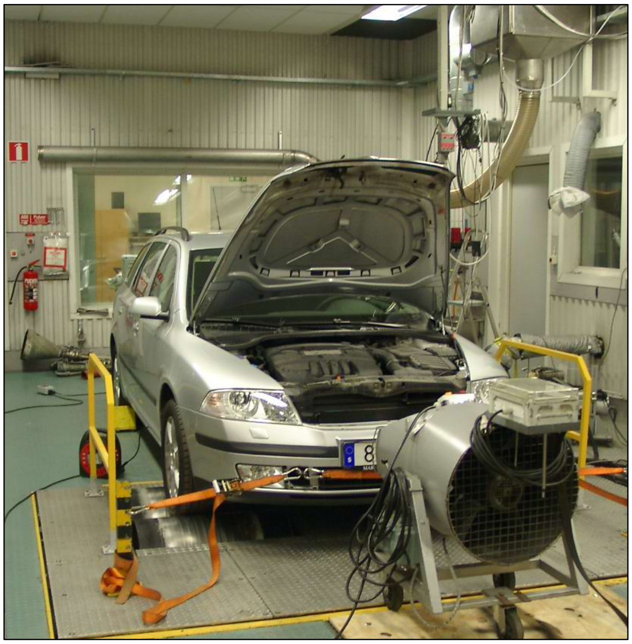


Figure 54 The test vehicle on the chassis dynamometer.

Emission measurement and test results

Three tests were performed for each temperature setting.

Please note that the scales are different in the diagrams.

Hydrocarbons

The hydrocarbon emissions were measured with FID (regular settings for AVL MTC: detector temp 190℃, calibrated with propane).

Hydrocarbons are calculated using the density (0,619 g/dm^3) defined for the calculations of HC in Euro 4 emissions standard, the emission standard applicable to the tested vehicle. The hydrocarbons are measured by FID.

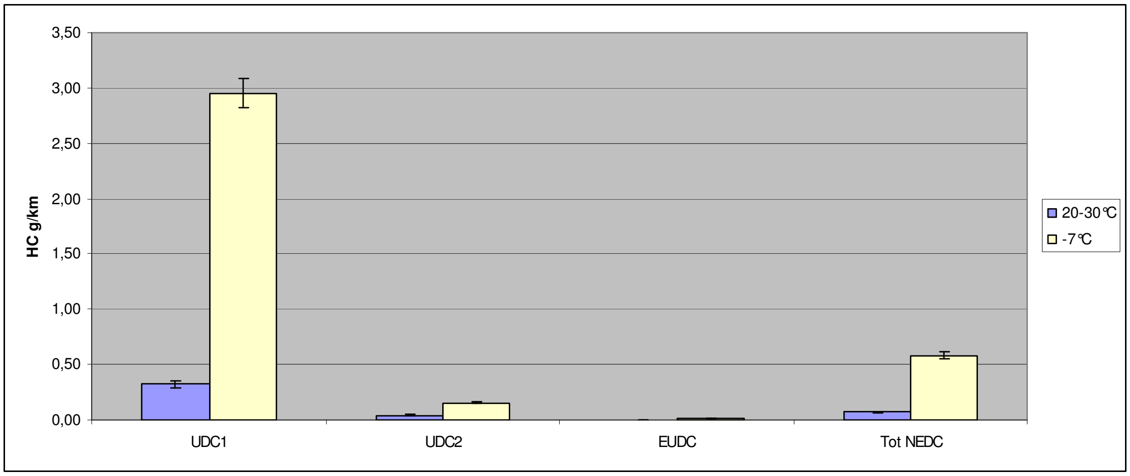


Figure 55 HC emissions, effect of different ambient temperatures, presented for each part of the NEDC and for total NEDC.

High levels of HC are emitted during the cold start phase. The pattern is the same for both temperatures, although the cold climate testing produces highly elevated emission levels.

Ethanol

Ethanol was analyzed with FTIR (Fourier Transform InfraRed), MS (Masspectrometer) and by the use of impingers. By using the FTIR and MS one can get second-by-second analysis of the ethanol emissions. The impingers collect through the total cycle, and the distilled water (containing the alcohol) is sent for analysis to an external laboratory.

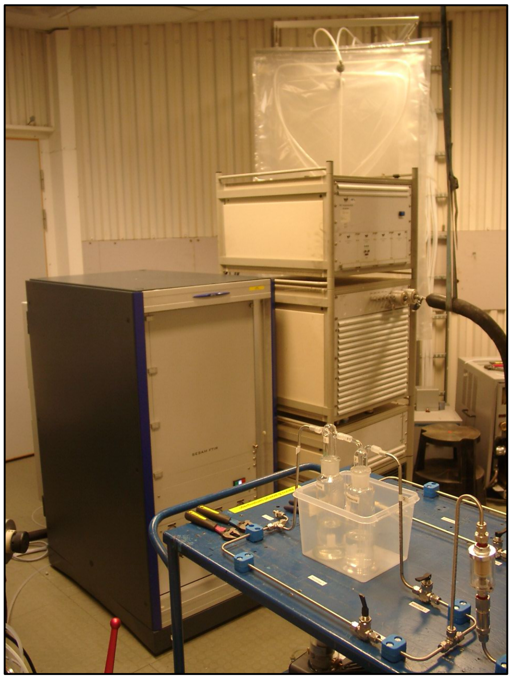


Figure 56 The FTIR, MS measurement systems and impinger sampling.

The MS and impinger system samples from the CVS tunnel. The FTIR samples from the raw emissions.

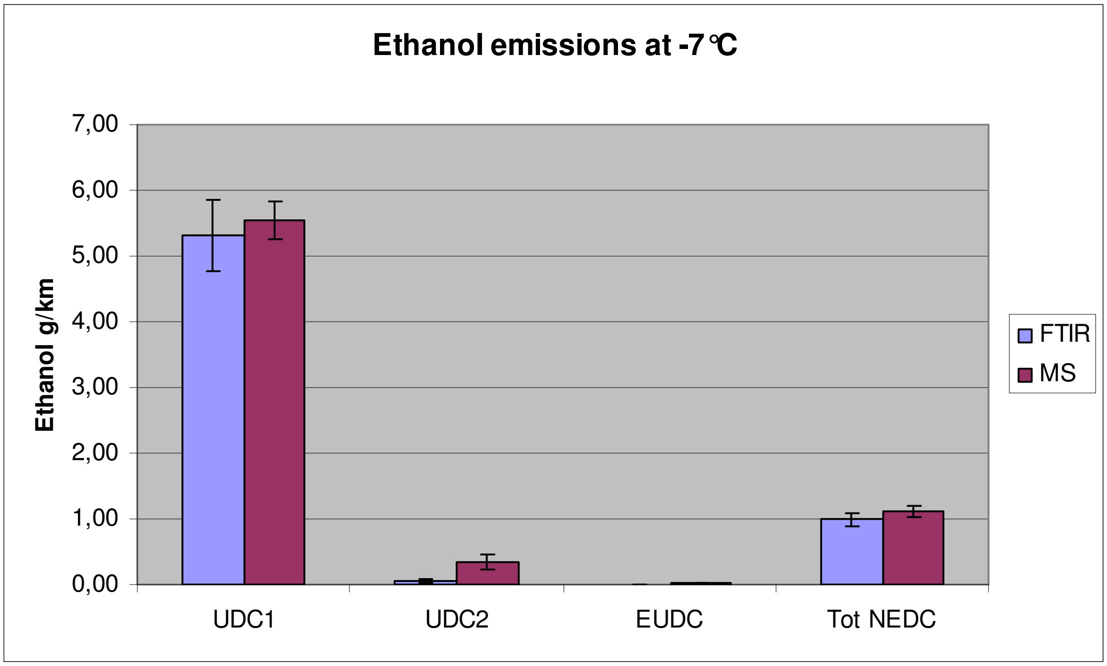


Figure 57 Ethanol emissions at -7°C, comparison between measurements performed with FTIR and MS. The different parts (UDC1, UDC2 and EUDC) and total of the NEDC cycle are presented.

The alcohol emissions are also (as well as the hydrocarbon emissions presented in Figure 55) temperature dependent, which is presented in Figure 58, where the tests performed at low ambient temperatures yields elevated alcohol emissions.
The ethanol emissions measured online by MS and FTIR can be observed in Figure 56. The correlation between the two instruments is good.

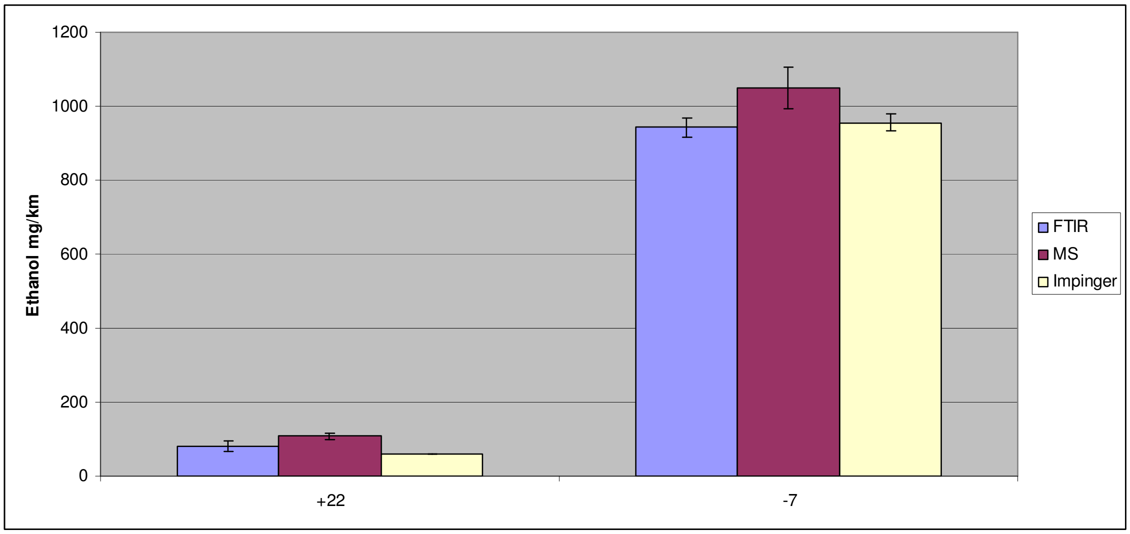


Figure 58 Ethanol emissions at two different test temperatures, NEDC test cycle. Comparison between measurements performed with FTIR, MS and the impinger sampling method.

Aldehydes

Aldehydes are formed in an oxidation reaction of primary alcohols, such as methanol (formaldehyde) and ethanol (acetaldehyde).

The aldehydes were analyzed online with FTIR and sampled in DNPH (2,4-dinitrophenyl hydrazine) cartridges. The FTIR gives second-by-second emissions, and the aldehydes sampled in the cartridges give a total value for the test cycle. After sampling the cartridges were sent to an external laboratory and analyzed with HPLC.

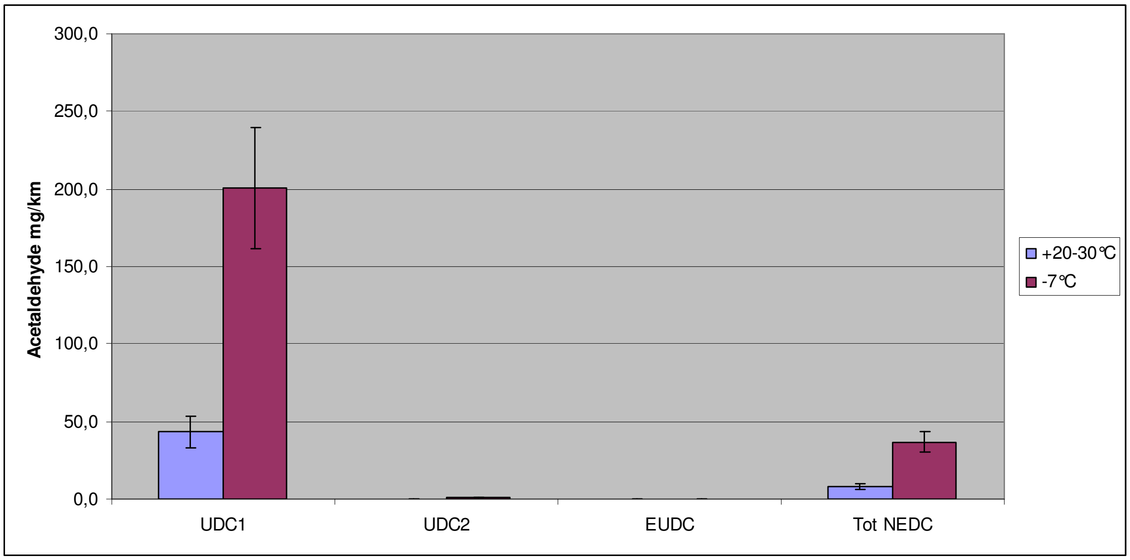


Figure 59 Acetaldehyde emissions in the different parts (UDC1, UDC2 and EUDC) of the NEDC cycle, and total NEDC – different ambient temperatures. Acetaldehyde concentration was measured with FTIR.

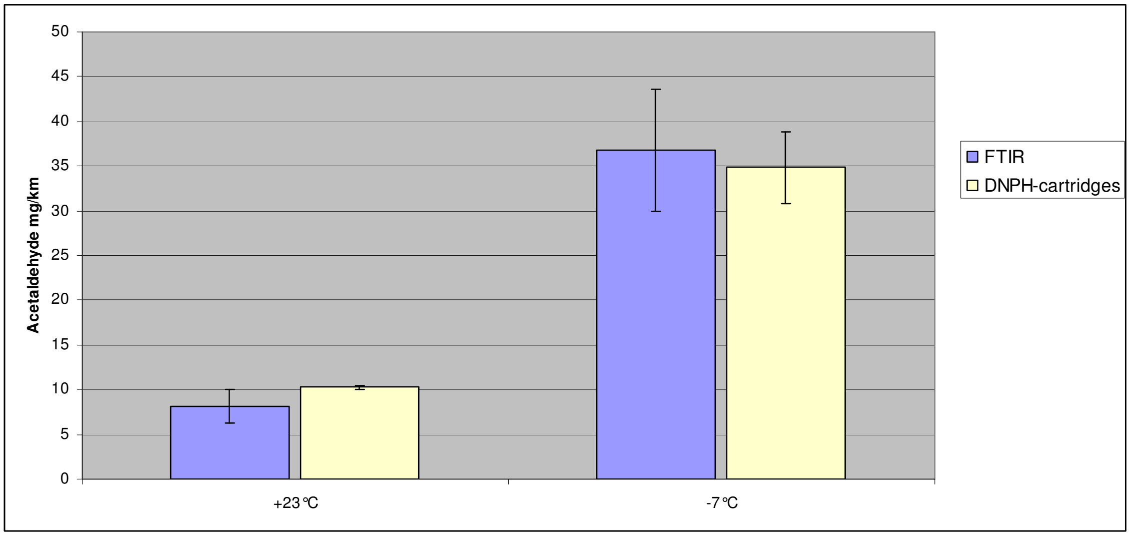


Figure 60 Acetaldehyde emissions at two different test temperatures, NEDC test cycle. Comparison between measurements performed with FTIR and DNPH-cartridges sampling method.

FID response to Ethanol

In the European regulation, the FID is assumed to respond to all hydrocarbons identically as it responds to propane in determining the concentration of carbon atoms in a gas sample.

In the US EPA regulation, the difference in response is taken into account and response factors are established for oxygenated hydrocarbons and methane. The measurements are thereby corrected for the presence of these compounds in the measured exhaust. Measured response factors are determined for each compound known to be present, and to affect, the FID response.

Response factors should be measured directly on the FID instrument being used for HC measurement. Note that FID response to ethanol may be slow due to ethanol adsorpion on walls of supply tubing. This should be taken into account when determining FID response and when determining sample time for THC measurement to be certain an accurate response to ethanol is obtained.

According to US EPA, the FID response factor to methanol is calculated as follows:

$$r = FIDppm / SAMppm$$

r = FID response factor
FIDppm = FID reading in ppmC
SAMppm = methanol concentration in the sample, or gas bottle, in ppmC

In Europe, the hydrocarbon emissions are measured with a Flame Ionization Detector (FID). For spark-ignition engines there are no specifications for FID temperature. For compression ignition engines the FID detector together with valves, pipework etc must be heated to 463 K (190 ºC) which is defined as HFID (Heated FID). It is therefore common that test laboratories have a detector temperature of 190 ºC as default setting.

In the US EPA regulation the FID detector must be set to 113 ºC when testing an alcohol-fuelled vehicle. This is based on the higher water vapour of methanol, and the fact that methanol can undergo decomposition reactions if the oven is too hot.

We have studied the influence of FID detector temperature and compared 113 ºC with 190 ºC. This comparison is presented in Figure X. A gas bottle with known concentration of ethanol was used.

5.1.3 Experimental

A gas bottle (with known concentration of ethanol) was connected to the sampling bag inlet, and the sampling bag was filled with the gas. The FID instrument was thereafter used to analyze the sampling bag. No time limit was set, all gas in the bag was analyzed.

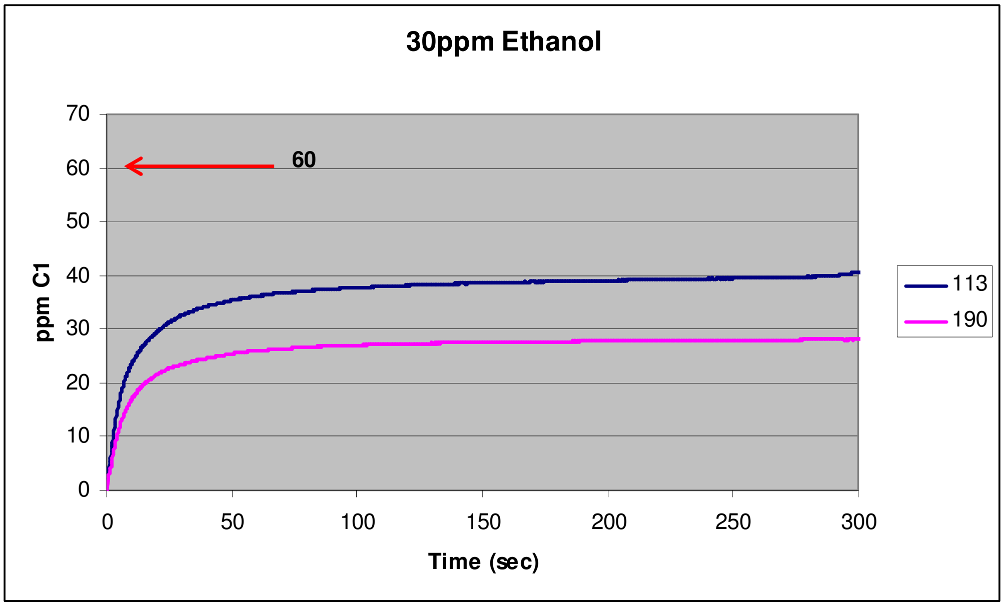


Figure 61Comparison of FID response curve due to different FID temperatures. In this figure, a 30 ppm ethanol gas bottle is presented. The arrow points out the actual concentration of C1 in the ethanol gas.

The FID response curve for ethanol is prolonged, which can be observed in Figure 61. This is due to ethanol adsorption in the measurement system.

If the concentration after a sampling time of 90 seconds is used, the response factors for the different temperatures are:

Rf: 0,67 (113 ºC)
Rf: 0,48 (190 ºC)

5.2 Low ethanol blends - E5-E25

Ethanol fuel mixtures have "E" numbers which describe the percentage of ethanol in the mixture by volume. for example E5 is 5% ethanol and 95% gasoline. Alternatively the term gasohol is used and usually refers to E10.

The practice of low volume blending of ethanol in gasoline is no novelty to the automotive industry. It has been utilized for several reasons. During the 1970:ies oil crises ethanol blends was used in the US as a domestic complement to fossil fuel. California and other US states use low ethanol blends in order to reduce smog, ethanol replaced MTBE as oxygenate as MTBE was banned in US in 2006 and recently increased ethanol contents in European gasoline from E5 to E10 has been allowed to reduce the emission of fossil carbon dioxide.

The most commonly used blends are E5 (Europe, Canada and India), E7 (Costa Rica and Brazil), E10 (Australia, Canada, China, Thailand, France and US) and E20 (Brazil and Thailand).

The drawbacks of ethanol blending are above all increased evaporative emissions and possible durability problems, see 5.3.1 and 5.3.10.

5.3 Consequences of increased ethanol contents in gasoline

Ethanol, C_2H_5OH has different properties from gasoline. Ethanol has higher octane number, higher latent heat of evaporation and different stoichiometric air fuel ratio. In addition and contrary to gasoline ethanol has a high affinity to water.

	Gasoline	Ethanol
Octane number (RON)	~95	~102
Density (g/cm^3)	0.74	0.79
Heat of combustion (MJ/kg)	42.4	26.8
Stoichiometric air fuel ratio	14.3	9.0
Boiling point (ºC)	-	78.5
Latent heat of evaporation (kJ/kg)	420	845

Table 21 Some gasoline and ethanol properties

When blending ethanol and gasoline the properties of the resulting fuel can be very different from that of the constituents. One example is the reid vapour pressure, shown as a function of ethanol contents in Figure 62.

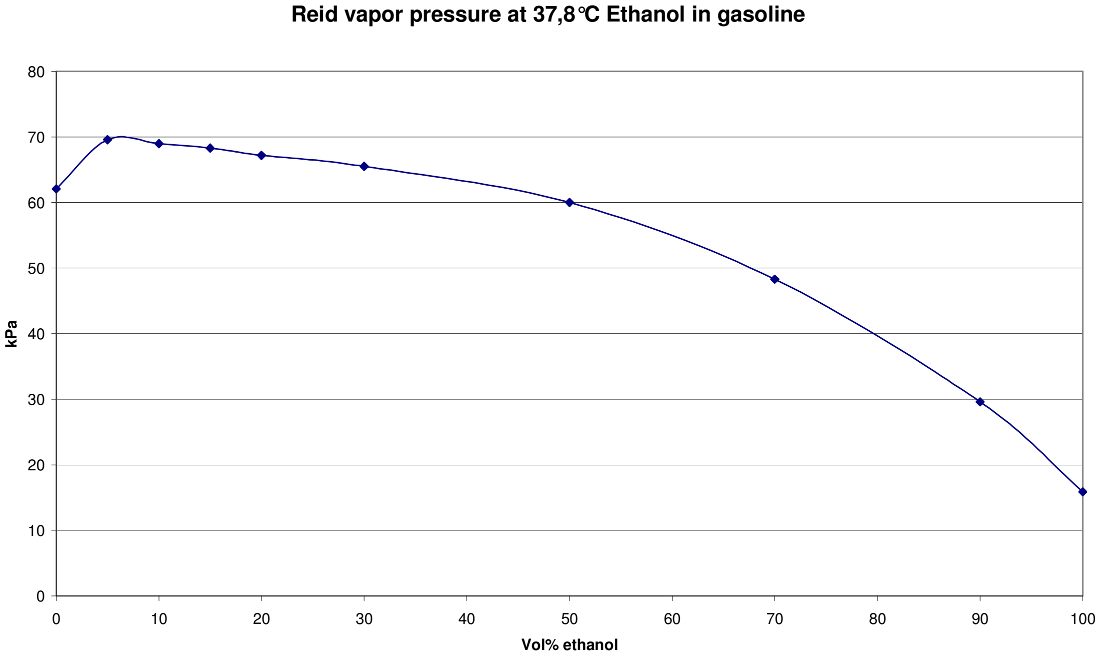


Figure 62 Reid vapour pressure for ethanol-gasoline blends. Source: SEKAB

5.3.1 Evaporative emissions

Evaporative emissions is fuel or fuel component vapour that escape the fuel system outside the cylinders. This occurs for instance while refuelling and when the fuel system is exposed to increasing temperature.

5.3.2 Diurnal breathing loss - DBL

Ethanol blending in fuel systems designed for gasoline increases the diurnal breathing loss over E0 at least in the span of E3-E20 most likely as a result of higher RVP but it could also be caused by elastomers reacting on ethanol [39], [48]. Most evidence suggest that the increase is significant. FFV systems designed to operate with E85 perform better with E85 than with E0. Also the ethanol content in the escaped vapour is shown to be unproportionally high. Fuel systems exposed to ethanol will continue to emit ethanol containing vapour for some time even after the system is drained and refuelled with E0 [39].

5.3.3 Hot soak loss – HSL

The contribution from hot soak test is generally relatively small compared to the diurnal test [49], see Figure 63. A weak trend towards increasing emissions is shown as the ethanol content in the fuel is increased [39] as shown in Figure 64.
Older cars do not seem to perform relatively worse in DBL or HSL tests with ethanol blends than do new cars.

5.3.4 Refuelling loss

A slight increase in refuel loss is seen with low grade ethanol blendes as a result of the higher Reid vapour pressure, RVP. However when RVP is adjusted to the same level as the reference gasoline, refuel loss for ethanol blends (E3 and E10) has been shown to decrease below the levels for the reference gasoline [49]

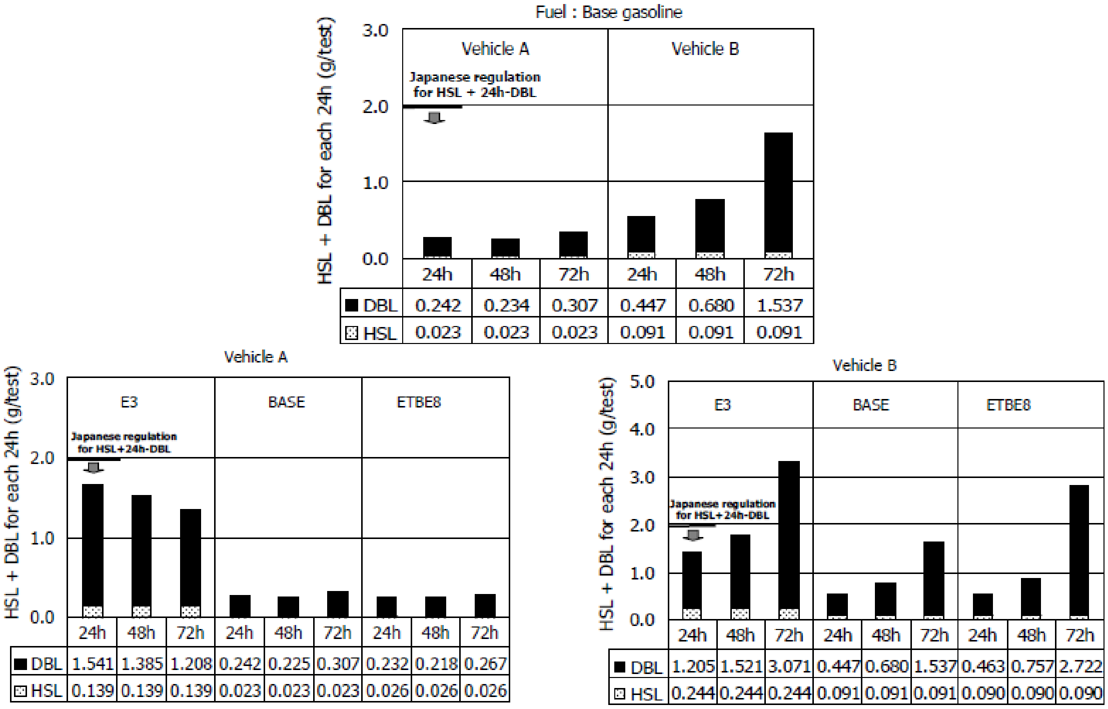


Figure 63 Comparison of HSL and DBL contribution to evaporative emissions from two cars.[49]

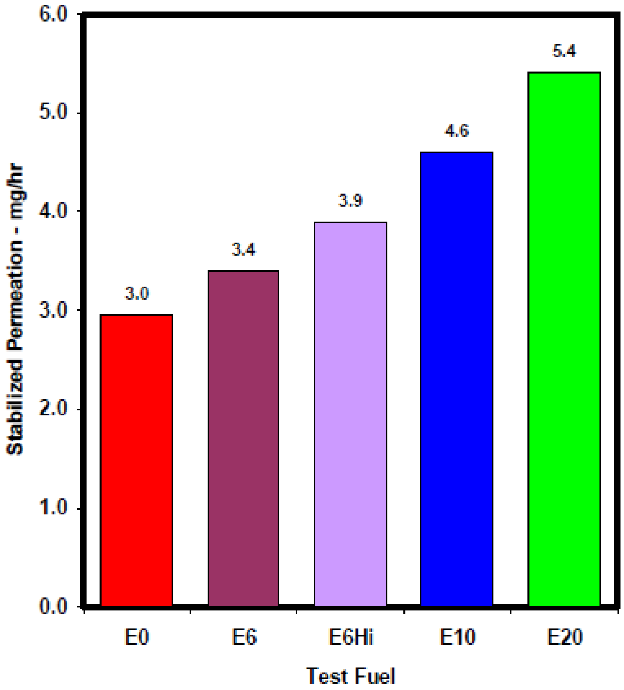


Figure 64 HSL with different ethanol containing gasoline blends. H6Hi has increased aromatics contents. [39]

5.3.5 Enleanment

Due to the fact that ethanol carry some of it's required oxygen for stoichiometric combustion ethanol require less air for the same amount of fuel than gasoline. For every 10 vol% ethanol added to pure gasoline an extra 4,5 mass% fuel is needed for stoichiometric mix. This results in enleanment of the combustion for engines optimized for gasoline operation, especially with older engines with no fuelling feedback system (lambda sensor). Engines designed to operate close to the lean limit can suffer from overheating which can result in engine damage. Engines that suffer from enleanment produce higher exhaust temperature which can shorten the catalytic converter light-off time.

More recent engine management systems (EMS) usually compensate for these effects by increasing the fuel flow at low power output and adjusting ignition timing and when applicable charging pressure. At higher power output however the fuel system becomes undersized if no mechanical modification is done and therefore the combustion becomes increasingly lean.

5.3.6 Engine performance

Low ethanol content have a positive effect on engine torque due to more efficient combustion caused by the oxygenate and higher octane number. How well this potential is utilized is however largely dependent on the EMS.

5.3.7 Fuel consumption

Ethanol has a lower latent heat of combustion than gasoline (see Table 21) which by itself would increase fuel consumption. However, the oxygen content enhance combustion efficiency. Figure 65 shows specific fuel consumption and thermal efficiency as functions of ethanol content. It is clear that SFC decrease with ethanol content up to about 20 vol% when the thermal efficiency curve starts to flatten out and is no longer sufficiently strong to compensate for the lower latent heat of combustion.

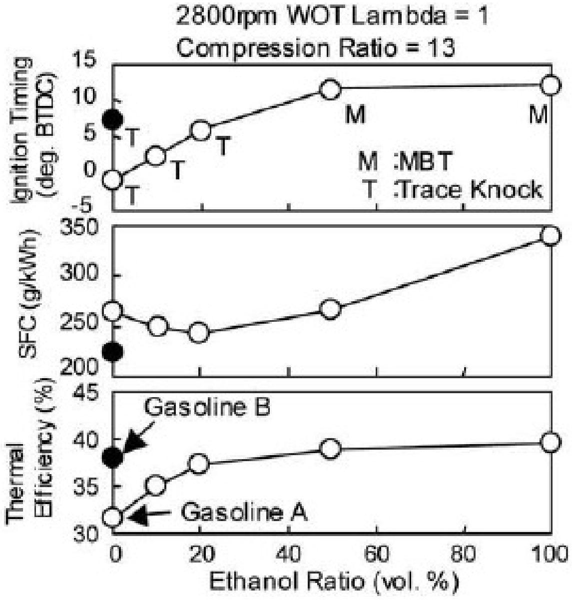


Figure 65 Effects of ethanol contents on thermal efficiency and specific fuel consumption. Note the high compression ratio. Gasoline A 92 RON, Gasoline B 100 RON. [52]

Engines with an active anti-knock strategy and especially turbocharged engines benefit from the higher octane number. Recent tests with a turbocharged Skoda Octavia suggest a slight decrease in fuel consumption over a wide velocity span when operating on E10 compared to premium gasoline. This is shown in Figure 66.

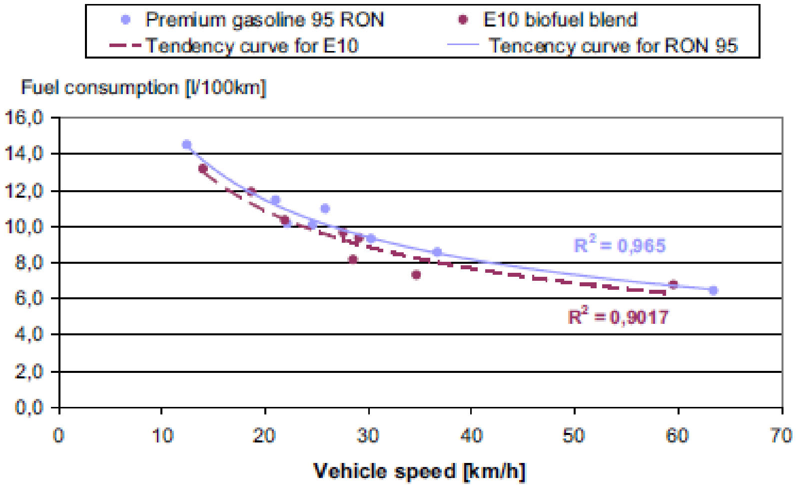


Figure 66 Fuel consumption of a Skoda Octavia driven in urban traffic conditions with gasoline and E10. [55]

5.3.8 Exhaust emissions

NOx

From the simplified chemical balances below it can be deducted that ethanol has about 30% more tri-atomic molecules in the combustion products than gasoline. This means that ethanol's combustion gas heat capacity is larger than that of gasoline, the same effect as is exploited with EGR. Thus the compressed gas temperature is decreased and hence the NOx formation.

Gasoline combustion:

$$C_7H_{13.3} + 10.33(O_2 + 3.785N_2) \rightarrow 7CO_2 + 6.66H_2O + 39.10N_2 + 4.19\ MJ$$

Ethanol combustion:

$$3.44C_2H_5OH + 10.33(O_2 + 3.785N_2) \rightarrow 6.88CO_2 + 10.32H_2O + 39.10N_2 + 4.24\ MJ$$

A 50% cut in NOx emissions with E10 relative to gasoline emission levels was reported by the team that investigated a Skoda Octavia [55].

CO_2, CO and HC

A slight reduction in carbon dioxide as an effect of ethanol content due to higher thermal efficiency and ethanol's higher H/C ratio is often reported. HC and CO is often reduced and it is assumed that it is due to that ethanol contrary to gasoline does not have components which boil at high temperature. E10 proved not to have any significant effect on CO and CO2 emission in the Skoda Octavia study [55].

The above presented effects of ethanol require that the EMS adapts the ignition to the fuel. NOx formation can be increased with fuel ethanol content if a high lambda results in significantly higher combustion temperature and the carbon containing emissions can be increased as a result of poor combustion. Figure 67 shows how NOx, THC and CO_2 is reduced with ethanol content.

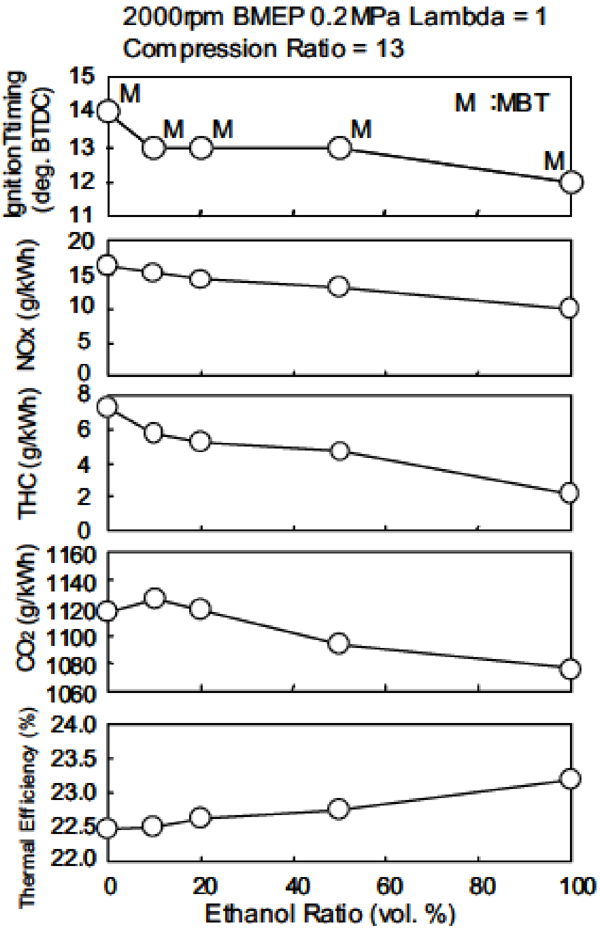


Figure 67 Effects of ethanol content on emissions. Note the high compression ratio. [52]

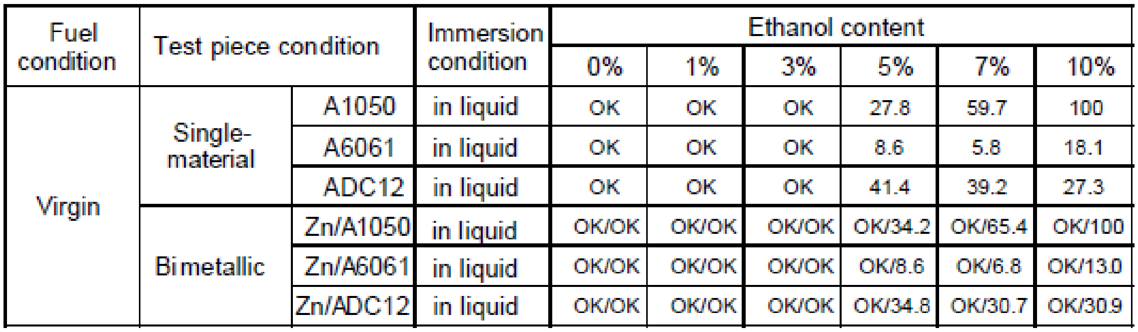
5.3.9 Phase separation

Ethanol is significantly more affined to water than to gasoline resulting in uptake of water whenever it is present. Since water and gasoline do not mix, this results in a stratification of the fuel with the ethanol-water phase at the bottom of the fuel tank. Thus, fuel from the bottom of the tank is pumped into the engine could cause engine damage. However, build on years of experience this concern has been minimized. Only with considerably large amounts of water in the tank will phase separation occur. Also solubility improvers such as isopropanol can prevent this problem [56].

5.3.10 Material compatibility

Due to ethanol’s higher affinity to water acetic acid, CH_3COOH can be formed rendering ethanol blended fuels slightly acidic. This in turn can pose corrosion problems on mechanical components made of copper, brass, steel and aluminium. A 720 hour immersion test at 100ºC shows massive corrosion or complete dissolution of aluminium parts at an ethanol content of 7% or more [54]. See Table 22.

Ethanol can also react with rubber and other elastomer components such as seals, gaskets and hoses, and cause them to swell and lose tensile strength which can result in fuel leakage and fuel pump failure. Manufacturers of hoses for gasoline dispensers have indicated that their products are suitable for gasoline ethanol blends containing up to 10vol% ethanol.



Fuel condition	Test piece condition		Immersion condition	Ethanol content					
				0%	1%	3%	5%	7%	10%
Virgin	Single-material	A1050	in liquid	OK	OK	OK	27.8	59.7	100
		A6061	in liquid	OK	OK	OK	8.6	5.8	18.1
		ADC12	in liquid	OK	OK	OK	41.4	39.2	27.3
	Bimetallic	Zn/A1050	in liquid	OK/OK	OK/OK	OK/OK	OK/34.2	OK/65.4	OK/100
		Zn/A6061	in liquid	OK/OK	OK/OK	OK/OK	OK/8.6	OK/6.8	OK/13.0
		Zn/ADC12	in liquid	OK/OK	OK/OK	OK/OK	OK/34.8	OK/30.7	OK/30.9

Table 22 Result from immersion test with aluminium in ethanol blended gasoline. The numbers in the table are the mass decrease ratio in % as a result of immersion [54]

5.3.11 Cold start performance

Ethanol's severe issues regarding cold startability is well recognized and well explained by Figure 68. Here stoichiometric air fuel ratio is showed as a function of ambient temperature for isooctane (here representing gasoline), methanol and ethanol. While isooctane is in stoichiometric mix in saturated vapour at as low temperature as about 0ºC the same point for ethanol is reached as high as about 25ºC. Furthermore ethanol is a single component which means that it has a fixed boiling point.

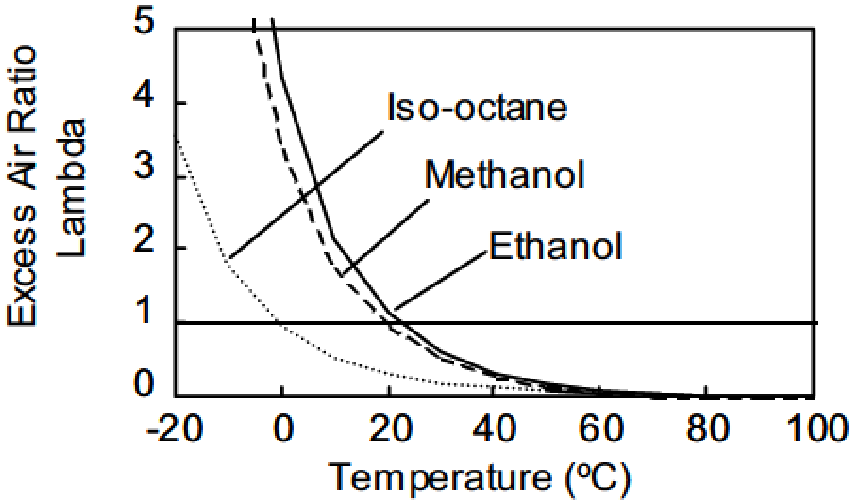


Figure 68 Ambient temperature effect of lambda of saturated vapour under ambient pressure 101 kPa. [52]

5.3.12 Vapour lock

Although the vapour pressure of pure ethanol is low, ethanol blending increases Reid vapour pressure (RVP) of low grade ethanol blends as described by Figure 62. This in turn increases the risk of vapour lock in warmer climates.

6 WORLDWIDE HARMONIZED LIGHT VEHICLES TEST PROCEDURE

The worldwide harmonized light vehicles test procedure - WLTP aims to establish a worldwide test procedure to measure light vehicle emissions and energy consumption.

According to a proposal from 10 June 2009 the work has been divided into three phases:
Phase 1 work (should be finished by the end of 2013)
(i) worldwide harmonized light duty driving cycle and associated test procedure for common measurement of pollutants, CO2 and fuel consumption and compatible for OBD demonstration
(ii) Develop OCE test procedure (Postponed)
(iii) Develop MAC test procedure (Postponed)
Phase 2 work
(i) Low ambient temperature / high altitude test procedure;
(ii) Durability
(iii) In-service conformity
(iv) OBD
Phase 3 work (work will start 2018)
(i) Emission limit values and OBD thresholds
(ii) Reference fuel properties
(iii) Correlation with existing regional cycles

The initial focus is on establishing a harmonized driving cycle (subgroup DHC) and test procedure (subgroup DTP). The goal is to complete both tasks by the end of 2013. DHC has had one informal meeting in Brussels 7-9 September 2009. The group is currently working on a methodology to develop the drive cycle. A draft was presented 30 October 2009.
In a proposal the following four work streams were presented

a. In-use data collection
b. Determination of weighting factors
c. Data analysis and drive cycle development
d. Validation/confirmation testing

Work streams c. and d. will be iterative and collaboration with DTP is pointed out as required hence a joint meeting is planned in June 2010.

In-use data collection will take place in seven regions; China, EU, India, Japan, South America (FIA), South Korea and USA. It will involve passenger cars and light commercial vehicles driving in urban and rural areas and on motorway.

Suggested definitions:
Urban: Paved roads in urban areas with a speed limit ≤50 km/hour (exclude mountain areas)
Rural: Paved non-motorways outside and inside urban areas with a speed limit between 50 and 100 km/hour (exclude mountain areas)
Motorway: Paved motorways (multi-lane roads specifically constructed and controlled for fast traffic)

The use of weighting factors, determined by total number of vehicle hours per region, used to weight data from regions when creating the unified distributions will probably be used. At the first DHC meeting, India and China raised objections to determining regional weighting factors based on current vehicle hours in each region. It was agreed to note these objections.

In-use data collection is currently executed on 20 vehicles in daily traffic in Sweden.

The DTP subgroup appear not to have had any meetings up until October 2009.

7 CONCLUSIONS

Below will follow the conclusions drawn from the respective subsections of this report.

7.1 The challenges of a cold climate

A cold climate poses other challenges to car manufacturers than do a hot climate. California has already founded regulations (CARB) to specifically target the particular problems with heat but we have yet to see corresponding and widely accepted regulations to target the problems that raise with subzero temperatures.

As shown in this report CI engines are not insensitive to ambient temperature as sometimes presumed. In the effort to reduce automotive emissions steps could be taken to reduce the contribution from CI engine cold starts by rethinking the CI engine certification procedure.

7.2 Aftertreatment systems

While gasoline engines are more sensitive to ambient temperature during warm-up than are diesel engines, gasoline engines, ones warmed up emits very low amount of regulated gases. Diesel engines on the other hand continue to emit particularly nitrous oxides throughout the entire operation. This results in the diesel engine being a worse polluter from a NO_x perspective while the high efficiency relative to SI engines makes it a more CO_2-efficient solution.

7.3 Evaporative emissions

In an evaporative emissions test with three used Swedish market cars all vehicles fulfilled the EC requirement with E10 fuel. However only one, equipped with a US market evaporative emissions system, passed the EPA emissions test and none of the cars fulfilled the even firmer CARB requirements.
The present results can not tell whether the US requirements can be fulfilled with E0.

During the CARB evaporative emissions tests large amounts of HC evaporated from the test object causing an automated alarm to go off. In order to produce measurements from the last 24 hour period data had to be acquired manually.

The physical size of the charcoal canister influence time of canister breakthrough. A larger volume canister is able to adsorb more HC and consequently reduce the vehicles evaporative emissions with the same size tank. This was confirmed by the test results.

7.4 Ethanol

In particularly the US methane is sometimes treated separately from other hydrocarbon components in the emission legislation. With the increasing use of ethanol in fuels there may be time to raise the question whether a similar arrangement should be taken in regard to ethanol.

7.4.1 E85

The market for alternatively fuelled vehicles is growing and will probably continue to do so because of the CO_2 issue. For Sweden, ethanol is a suitable fuel that can be produced within the country. Besides the more dedicated vehicle configurations, all commercially available gasoline is blended with a smaller amount of ethanol.

When alcohols are used as blending components in gasoline, uncombusted alcohols from the fuel are emitted in the exhaust in various amounts. In the EU emission standard the ordinary test cycle is NEDC, which include start with a cold engine. At the engine start a high amount of uncombusted ethanol is emitted, and at cold climate testing the amount is even more elevated compared to testing at room temperature. In EU everything measured by a FID is considered to be hydrocarbons. Ethanol will also be registered by the FID, and E85 vehicles can have rather high hydrocarbon emissions, especially at cold climate testing. From 2011 the flexible fuelled vehicles will be tested both at room temperature and cold climate. The hydrocarbon density used for calculation of mass emissions has also been adjusted to the E85 fuel. The molecule is heavier, leading to a higher density. The consequence of this is an increase of approximately 50% in hydrocarbon emissions due to the calculation.

This might lead to difficulties for the ethanol fuelled FFVs to be certified according to Euro 5/Euro 6.

In other countries, such as Brazil and the USA where alcohol fuelled vehicles are commercially available, the legislation looks different. According to the US EPA alcohols and aldehydes are to be measured separately. A FID response factor is determined and the FID result is adjusted for the alcohol and aldehyde parts. In Brazil the vehicle manufacturer has the possibility to choose to measure alcohols separately and perform the same FID adjustments as in the US.

7.4.2 Consequences of increased ethanol contents in gasoline

The literature findings suggest increased evaporative emissions as a result of increasing ethanol contents from 5% to 10% in gasoline fuel. Such measure is also likely to reduce NO_x and fossil CO_2 emissions.

7.5 Worldwide Harmonized Light vehicles Test Procedure

WLTP is an international collaboration that aims at establishing a worldwide procedure for the measurement of light vehicle emissions and energy consumption. The work is expected to continue throughout this decade. In-use data from vehicles at several geographical locations is currently being collected. This will be the basis for a new chassis dynomometer driving cycle.

8 SUGGESTED FUTURE WORK

- There is little and sometimes contradicting results publicised on low temperature operation of SCR-systems

- The reductant used in SCR systems is prone to aging at high temperatures (>35ºC). OEMs claim to utilize sensors to monitor the reductant quality. It is however uncertain whether these sensors can discriminate fresh from aged reductant and to what extent the reductant can be allowed to age without loss of efficiency.

- In connection with the previous two points work should be done to better understand the real life characteristics of the reductant AdBlue® .Especially managing the urea dosing at subzero temperatures and the thawing of a completely frozen urea tank with respect to the risk of precipitation.

- Diurnal tests are designed for hot climates. A corresponding situation not covered by the diurnal test is a car driven at low temperature (subzero) and then parked in a garage where the temperature is approximately 10ºC.

- In the evaporative emissions test performed in this work only one individual each of three vehicle types was tested. For a more extensive knowledge and understanding further tests are necessary. These could also include sniffers at strategic locations such as the refuelling cap and canister in order to gain a more extensive understanding of the sources of evaporative emissions.

- The concept of hydrocarbon emissions needs to be further investigated and maybe even redefined particularly with regard to ethanol and ethanol blends. Exhaust components of FFVs need to be recognized and classified according to their environmental impact. For instance; should ethanol be treated as a hydrocarbon and could methane be treated as a green house gas together with carbon dioxide?

- The function, weaknesses and further development potentials of carbon canisters for hydrocarbon vapour adsorption are poorly covered in the publicised literature. With better management and purge strategies evaporative emissions could be decreased while maintaining good air fuel ratio control.

ABBREVIATIONS

ATV	All-terrain vehicle
BAFF	BioAlcohol Fuel Foundation
CARB	California Air Resources Board
CBG	Compressed biogas
CDPF	Catalyzed diesel particulate filter
CFR	Code of federal regulations
CNG	Compressed natural gas
CPF	Catalyzed particulate filter
CR	Compression ratio
DBL	Diurnal breathing loss
DI	Direct injection
DEF	Diesel exhaust fluid. Urea solution
DHC	Development of the harmonized driving cycle. WLTP subgroup
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DTP	Development of test procedure. WLTP subgroup
EGR	Exhaust gas recirculation
EP	End point
EPA	Environmental Protection Agency
EUDC	Extra urban driving cycle
EVAP	Evaporation/evaporative
FFV	Flex fuel vehicle
FTP	Federal test procedure
GTR	Global technical regulation
HC	Hydrocarbons

HC-SCR	Hydrocarbon selective catalytic reduction
HD	Heavy duty
HSL	Hot soak loss
IBP	Initial boiling point
LD	Light duty
LDT	Light duty truck
LDV	Light duty vehicle
LNC	Lean NOx catalyst
LNT	Lean NOx trap
LPG	Liquefied petroleum gas
MAC	Mobile air conditioning
NAC	NOx adsorber catalyst
NEDC	New European driving cycle
NYCC	New York city cycle
OBD	On-board diagnostics
OCE	Off-cycle emissions
OEM	Original equipment manufacturer
ORVR	Onboard Refuelling Vapour Recovery
PFI	Port fuel injection
PTC	Pre-turbocharger catalyst
PZEV	Partially zero evaporative emission vehicle
RME	Rapeseed oil methyl ester
RVP	Reid vapour pressure
SCR	Selective catalytic reduction
SFC	Specific fuel consumption
SIKA	Statens institut för kommunikationsanalys
SHED	Sealed housing for evaporative determination
SPI	Single point injection
TWC	Three way catalyst
UDC	Urban driving cycle
UDDS	Urban Dynamometer Driving Schedule
VOC	Volatile organic compound
WLTP	World harmonized light-duty test procedure

REFERENCES

[1] Statens Institut för Kommunikationsanalys, SIKA. Fordon 2008
[2] G. E. Andrews, G. Zhu, H. Li, A. Simpson, J. A. Wylie, M. Bell and J. Tate. The effect of Ambient Temperature on Cold-start Urban Traffic Emissions for a Real World SI Car Using In-vehicle Emissions Measurement in an Urban Traffic Jam Test Cycle. SAE 2004-01-2903
[3] P. Bielaczyc and J. Merkisz. Cold start Emissions Investigation at Different Ambient Temperature Conditions. SAE 980401
[4] J. K. Laurikko. Automotive Exhaust Emissions at Low Ambient Temperature. SAE 890003
[5] R. Payri, F. J. Salvador, J. Gimeno and G. Bracho. Understanding Diesel Injection Characteristics in Winter Conditions. SAE 2009-01-0836
[6] P. Pacaud, H. Perrin and O. Laget. Cold Start on Diesel Engine: Is Low Compression Ratio Compatible with Cold Start Requirements? SAE 2008-01-1310
[7] G. E. Andrews, H. Li, J. A. Wylie and G. Zhu. Influence of Ambient Temperature on Cold-start Emissions for a Euro I SI Car Using In-vehicle Emissions Measurement in an Urban Traffic Jam Test Cycle. SAE 2005-01-1617
[8] P. Aakko and N-O. Nylund. Particulate Emissions at Moderate and Cold Temperatures Using Different Fuels. SAE 2003-01-3285
[9] Regulation No 83 of the Economic Commission for Europe of the United Nations (UN/ECE)– Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements.
[10] European Union. Regulation No. 715/2007 of the European Parliament and Council. on Type Approval of Motor Vehicles with Respect to Emissions from Light Passenger and Commercial Vehicles (Euro 5 and Euro 6) and on Access to Vehicle Repair and Maintenance Information
[11] Environmental Protection Agency. CFR 40 Part 86 Control of Emissions from New and In-use Highway Vehicles and Engines.
[12] J. D. Hawirko and M. D. Checkel. Quantifying Vehicle Emission Factors for Various Ambient Conditions using an On-Road, Real-Time Emissions System. SAE 2003-01-0301
[13] H. Oguma, M. Koga, S. Momoshima, K. Nishizawa and S. Yamamoto. Development of Third Generation of Gasoline P-ZEV Technology. SAE 2003-01-0816
[14] J. A. Lupescu, T. B. Chanko, J. F. Richert and J. E. DeVries. Treatment of Vehicle Emissions from the Combustion of E85 and Gasoline with Catalyzed Hydrocarbon Traps. SAE 2009-01-1080
[15] T. V. Johnson. Diesel Emission Control in Review. SAE 2009-01-0121
[16] Ch. LeTavec, J. Uihlein, K. Vertin, S. Chatterjee, S. Wayne, N. Clark, M. Gautam, G. Thompson, D. Lyons, K. Hallstrom, K. Chandler and T. Coburn. Year-Long Evaluation of Trucks and Buses Equipped with Passive Diesel Particulate Filters. SAE 2002-01-0433

[17] T. Maunula, P. Matilainen, M. Louhelainen, P. Juvonen and T. Kinnunen. Catalyzed Particulate Filters for Mobile Diesel Applications. SAE 2007-01-0041

[18] B. Carberry, G. Grasi, S. Guerin, F. Jayat and R. Konieczny. Pre-Turbocharger Catalyst – Fast catalyst light-off evaluation. SAE 2005-01-2142

[19] R. Konieczny, W. Müller, B. Cherington, M. Presti, F. Jayat, M. J. Davies and P. R. Murphy. Pre-Turbocharger-Catalyst – Catalytic Performances on an Euro V Type Diesel Engine and Robust Design Development. SAE 2008-01-0768.

[20] F. Jayat, L. Pace and R. Konieczny. Vorturboladerkatalysatoren – Anforderungen aus aufladetechnischer Sicht sowie zukünftiger, innovativer Abgasnachbehandlungskonzepte. Emitec.

[21] P. Tennison, Ch. Lambert and M. Levin. NO_x Control Development with Urea SCR on a Diesel Passenger Car. SAE 2004-01-1291

[22] A. E. El-sharkawy, P. D. Kalantzis, M.A. Syed and D. J. Snyder. Thermal Analysis of Urea Tank Solution Warm Up for Selective Catalytic Reduction (SCR)

[23] K. Hirata, N. Masaki, H. Ueno and H. Akagawa. Development of Urea-SCR System for Heavy-Duty Commercial Vehicles. SAE 2005-01-1860

[24] J. A. Jura, J. Girard, G. Cavataio, C. Montreuil and Ch. Lambert. Cold Start Performance and Enhanced Thermal Durability of Vanadium SCR Catalysts. SAE 2009-01-0625

[25] C.L. DiMaggio, G.B. Fisher, K.M. Rahmoeller and M. Sellnau. Dual SCR Aftertreatment for Lean NOx Reduction. SAE 2009-01-0277

[26] Ch. Lambert, R. Hammerle, R. McGill, M. Khair and Ch. Sharp. Technical Advantages of Urea SCR for Light-Duty and Heavy-Duty Diesel Vehicle Applications. SAE 2004-01-1292

[27] Borealis. Technical Data Sheet AdBlue®

[28] G. R. Maxwell. Synthetic nitrogen products: a practical guide to the products and processes

[29] C. S. Sluder, J.M.E. Storey, S.A. Lewis and L.A. Lewis. Low Temperature Urea Decomposition and SCR Performance. SAE 2005-01-1858

[30] J. W. Girard, G. Cavataio and Ch. K. Lambert. The Influence of Ammonia Slip Catalysts on Ammonia N_2O and NO_x Emissions for Diesel Engines. SAE 2007-01-1572

[31] J. Thompson, J. O. Beeck, E. Joubert and T. Wilhelm. Case Study of Urea SCR Intergration on Passenger Cars Monitoring of Urea Inside the Tank During Hot and Cold Evironment Test Missions. SAE 2008-01-1181

[32] C. Enderie, G. Vent and M. Paule. BLUETEC Diesel Technology – Clean, Efficient and Powerful. SAE 2008-01-1182

[33] H. Karlsson, J. Gåsste and P. Åsman. Regulated and Non-regulated Emissions from Euro 4 Alternative Fuel Vehicles. SAE 2008-01-1770

[34] J. Merkisz, J. Pielecha and W. Gis. Gasoline and LPG Vehicle Emission Factors in a Road Test. SAE 2009-01-0937

[35] D. Kawano, H.Ishii and Y. Goto. Effects of Biodiesel Blending in Emission Characteristics of Modern Diesel Engine. SAE 2008-01-2384

[36] K. Yoshida, S. Taniguch, K. Kitano, Y. Tsukasaki, R. Hasegawa and I. Sakata. Effects of RME30 on Exhaust Emissions and Combustion in a Diesel Engine. SAE 2008-01-2499

[37] California evaporative emission standards and test procedures

[38] O. A. Usman and M. Usman. Recent Advances in Reducing Fuel Permeability and Leakage into the Environment from Automotive Fuel Systems. SAE 2001-01-2484

[39] H. M. Haskew, P. E. Thomas, F. Liberty and D. McClement. Fuel Permeation from automotive systems: E0, E6, E10, E20 and E85. CRC Report No. E-65-3

[40] M. Beecham. RESEARCH ANALYSIS: Fueling Opinions in the Tank Market. Just-Auto.com editorial team

[41] Y. Iriyama, M. Kobayashi, T. Matsubara, Y. Nishimura, R. Nomura and T. Ishikawa. Design of a Fuel Vapor-containment System (FVS) to Meet Zero Evaporative Emissions Requirements in a Hybrid Electric Vehicle. SAE 2005-01-3825

[42] T. Arase, T. Ishikawa, M. Kobayashi, Y. Hyodo, M. Kasai and N. Nakano. Development of Vapor Reducing Fuel Tank System. SAE 2001-01-0729

[43] H. Itakura, N. Kato, T. Kohama, Y. Hyoudou and T. Murai. Studies on Carbon Canisters to Satisfy LEV II EVAP Regulations. SAE 2000-01-0895

[44] S. Flora, S. Schaffer and T. Arruda. Humidity Effects on a Carbon Hydrocarbon Adsorber. SAE 2009-01-0873

[45] A. Molnar, J. Baker, P. Tucker and D. Bilbrey. Comparison of Fuel Hose SHED Test Results and Predicted Values Using Fundamental Material Barrier Properties. SAE 2002-01-0635

[46] H. J. Barager, R. L. Bell, M. R. Day, T. R. Earnest, Jr. Mc Bride, M. McBride, W. A. Khan and R. D. Stevens. Reduction of Hydrocarbon Permeation through SORE Oil Seal and Fuel System Components. SAE 2004-32-0027

[47] California Air Resource Board. Durability testing of barrier treated high-density polyethylene small off-road engine fuel tanks. June 21, 2002

[48] A. Kumar, D. S. Khatri and K. G. Babu. An Investigation of Potential Challenges with Higher Ethanol-gasoline Blend on a Single Cylinder Spark Ignition Research Engine. SAE 2009-01-0137

[49] H. Tanaka, T. Matsumoto, R. Funaki, T. Kato, K. Mitsutake, M. Sekimoto and H. Watanabe. Effects of Ethanol or MTBE Blending in Gasoline on Evaporative Emissions for Japanese In-use Passenger Vehicles. SAE 2007-01-4005

[50] M. Gogos, D. Savvidis and J. Triandafyllis. Study of the Effect of Ethanol Use on a Ford Escort Fitted with an Old Technology Engine. SAE 2008-01-2608

[51] A. A. Grisanti, T. R. Aulich and C. L. Knudson. Gasoline Evaporative Emissions – Ethanol Effects on Vapor Control Canister Sorbent Performance. SAE 952748

[52] K. Nakata, S. Utsumi, A. Ota, K. Kawatake, T. Kawai and T. Tsunooka. The Effect of Ethanol Fuel on a Spark Ignition Engine. SAE 2006-01-3380

[53] R. M. Shanmugam, N. Saravanan, L. Srinivasan, V. Hosur and S. Sridhar. An Experimental Investigation on 1.4L MPFI Gasoline Engine to Study its Performance, Emissions and Compatibility with E10 Fuel. SAE 2009-01-0611

[54] S. Soma, K. Nagai, K. Morita, G. Sugiyama and T. Seko. Investigations of Impact of the Ethanol Content on Exhust Gases, Fuel Evaporative Emissions,

High-temperature Drivability and Materials for the Supply System Parts of Gasoline Vehicles. SAE 2005-01-3710

[55] D. Tóth, L. Cachón, E. Pucher, T. Raetzsch, D. Weissenberger. Real World and Chassis Dynomometer Emission Measurement of a Turbocharged Gasoline Vehicle with Increased Bio Fuel Blend. SAE 2008-01-1768

[56] R. Waytulonis, D. Kittelson and D. Zarling. E20 Effects in Small Non-Road SI Engines. A Literature and Information Search. Report to the Minnesota Department of Commerce