

Diesel Vehicle Cold Operability: Design of Fuel System Essential Besides Fuel Properties

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ABSTRACT

Cold operability is estimated by fuel's cold filter plugging point (CFPP). However, correlation of CFPP with diesel vehicle performance originates from a period when simple in-line or distributor fuel injection systems were applied and fuels did not contain biocomponents. Today, common rail fuel injection systems are used and there seem to be remarkable differences in their design between vehicle models.

Seven cars were tested in a climate chamber. The best cars operated down to 8°C below fuel's CFPP but the worst get into problems 5°C above CFPP with the same fuel. It is challenging to define what CFPP is needed in order to guarantee trouble-free winter performance because there are big differences between car models. It is fundamental to get the fuel temperature of a vehicle's fuel filter above the fuel's cloud point during driving, and this depends on fuel system design factors, such as location and size of fuel filter and fuel heater if it is used.

Oil companies prefer diesel fuels which do not have unnecessary good cold properties because better cold properties reduce the diesel fuel yield at refineries at a time when there is shortage of diesel fuels in Europe. Light middle distillate fractions suitable for winter grades are needed also for aviation kerosene production. Cold operability problems related to biocomponents can be avoided by using isomerized HVO.

Trouble-free operation in cold conditions is important for all stakeholders: Oil companies, automotive companies and vehicle owners. Further exchange of information and co-operation between oil, automotive and fuel additive companies would be valuable as well as more vehicle testing.

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INTRODUCTION

Cold operability of diesel vehicles, as a function of fuel grade, is in principle a simple issue but in practice there are many points of views to be considered. Oil companies are technically able to produce diesel fuels which can operate in the most severe winter conditions. However, that is not practical since distillation range of winter grades has to be lighter than of summer grades which means that less diesel fuel is produced from a barrel of crude oil. An example of distillation characteristics is shown in [figure 1](#). In addition to that production of severe winter grades competes with the same molecule weight hydrocarbons which are needed for aviation kerosene markets.

As a consequence, winter grades are more expensive than summer grades; this additional cost is not at all desired especially by truck operators. An example of fuel prices is shown in [table 1](#). Market forces especially between mild and severe winters may change pricing since heating fuel oil is produced from the same refinery streams as diesel fuel. In

addition to that volumetric fuel consumption of winter grades is higher than that of summer or intermediate grades which makes winter grades less attractive for professional truck owners.

Any factors that reduce diesel fuel yield at refineries should be avoided because refining capacity and markets are not balanced in Europe which requires import of diesel fuel and export of gasoline. Oil companies also face new challenges because of the increased use of biocomponents, which do not always behave like fossil hydrocarbon fuels in cold conditions.

Decades ago diesel vehicles were mainly owned by professionals with the knowledge and capacity to take care of winter issues. In the most severe cases diesel vehicle owners might add some kerosene or gasoline into diesel fuel; such a measure might work temporarily in robust in-line or distributor type injection pumps. However, today sophisticated common rail fuel injection systems do not tolerate additional light fractions and vehicle owner's manuals

often strictly forbid adding of any gasoline into diesel fuel. In addition, kerosenes do not meet the current sulfur, cetane number and lubricity specifications set for diesel fuel by the European EN 590 standard.

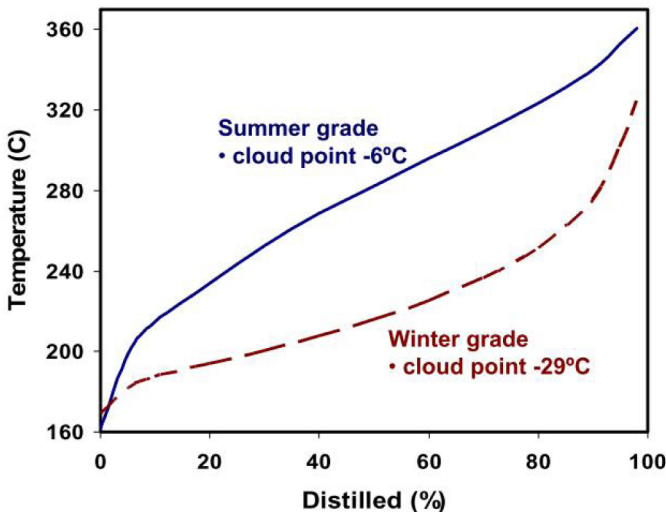


Figure 1. Distillation curves of summer and winter grade diesel fuels (source Neste Oil measurements).

Table 1. Properties of diesel fuels in Finland and their retail prices in January 2012 (Neste Oil's products as an example).

Grade	Cloud point (°C)	CFPP (°C)	Retail price (Eur/l)
Midsummer	≤ 0	≤ -10	(available only in mid summer)
Summer	≤ -5	≤ -15	1.45
Intermediate	≤ -15	≤ -25	1.48
Winter	≤ -29	≤ -34	1.50
Arctic	≤ -40	≤ -44	1.54

The diesel car population has been increasing in the past years in many European countries and it may even continue its growth due to the better fuel efficiency relative to gasoline models. Some cars may encounter low annual mileage raising new challenges since some summer grade diesel refueled during the autumn may still exist in car's fuel tank when winter comes.

Winter 2010 - 2011 was quite harsh in Finland. In January - February 2011 average officially recorded temperatures in southern Finland were about -10°C , central Finland -16°C and in the northern parts of the country -19°C . The lowest temperatures were accordingly about -25°C , -30°C and -39°C . Even lower temperatures may have been met outside the meteorological observation points. Vehicle operability at

such lowest temperatures is of particular importance because the fuel tank of a car has time to cool down to the lowest temperature during a night.

Although it is not economically feasible to design vehicles and fuels to operate in the most severe conditions that ever can be met, these temperatures give guidelines for which kind of climate conditions vehicles and fuels sold in Europe should be designed in order to keep goods and people moving. Advice for defining statistically proper fuel grades can be found from the US ASTM D 975 diesel fuel standard.

Packing of fuel tank into the car body and fuel system into the engine compartment is today so tight that bringing the car to a warm garage is the only solution if it stops because of fuel problems. A car can be loaded to a trailer or truck, but towing a truck or bus is challenging because brakes and power-steering are lost when engine is not running. So, cold operability is essential for drivers.

LOW TEMPERATURE CHARACTERISTICS OF DIESEL FUEL

Diesel fuel is a mixture of aromatic, paraffinic and naphthenic hydrocarbons of which paraffinic ones have limited solubility in the fuel in low temperatures. When fuel is cooled down some of the paraffins will come out in the form of paraffin wax crystals. Size of the crystals in commercial fuels treated with cold flow additives is roughly $50\text{ }\mu\text{m}$ depending on fuel composition, time exposed to the cold and cold flow additives used [3]. Average pore size of fuel filters in vehicles was about $8 - 10\text{ }\mu\text{m}$ with in-line fuel injection pumps and $4 - 5\text{ }\mu\text{m}$ with distributor pumps [1, page 507-]. Today when common rail fuel injection systems are used filters pore sizes are even tighter than with distributor pumps. When crystals sizes of paraffins and filter pore sizes are compared to each other, it is clear that if crystals exist in the fuel, they clog filters sooner or later during the drive.

Cold properties of diesel fuel are commonly described through the terms of cloud point, Cold Filter Plugging Point (CFPP) and pour point [9, page 419-].

Cloud Point

Cloud point is the temperature at which clouds of paraffin crystals first appear when a fuel is cooled down. Above the cloud point a high quality hydrocarbon fuel is clear and bright liquid which flows through filters without any troubles. Problems may appear only if fuel contains free water, insoluble additives or impurities. However, vehicles usually operate at temperatures clearly below cloud point which means that cloud point underestimates the lowest operability temperature [9, page 421]. Cloud point can be measured by EN 23015 method.

Pour Point

When diesel fuel is cooled down further it turns into a gel state which does not flow any more in a test jar. This is

measured by pour point test where fuel is cooled down at 3°C intervals and the latest temperature where fuel was able to flow is named to the pour point. It is measured by ISO 3016 method. However, pour point cannot be used for estimating the lowest temperature for vehicle operability since pour point value is clearly over-optimistic [9, page 421].

CFPP

During the 1960's and 1970's CFPP test was developed in Europe in order to correlate fuel production specification with statistical data from real diesel vehicle operability. CFPP test itself does not represent fuel filter of a vehicle since it consists of a screen with a mesh size of 45 µm but during the past CFPP's correlation to vehicles was satisfactory [9, page 461-]. CFPP method is standardized by EN 116 and EN 16329.

Other Tests

In North America Low-Temperature Flow Test (LTFT) is used besides CFPP. Also some new developments like Simulated Filter Plugging Point (SFPP) have been proposed to complement or replace CFPP but they have not been successful until now.

One challenge of all of these tests is that they are rapid laboratory tests. In practice cooling down may take days and cold periods may last for weeks or even months.

Viscosity

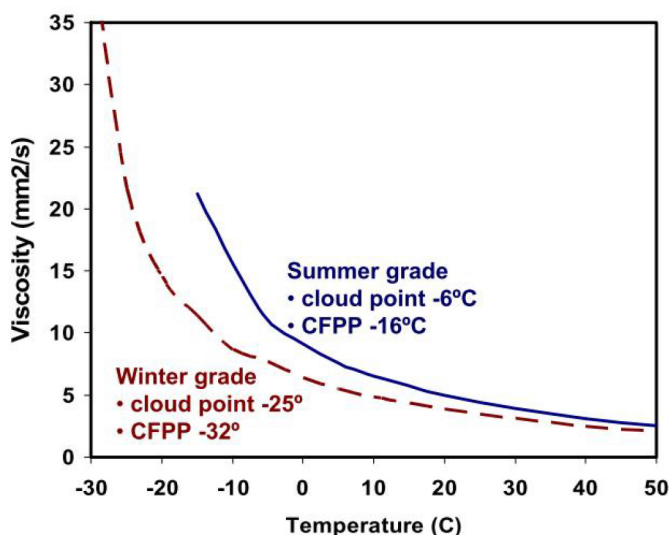


Figure 2. Viscosity of summer and winter grade fuels as a function of temperature (source Neste Oil measurements).

Viscosity depends strongly on temperature as seen from figure 2 and it has an effect on flow resistance in fuel pipes. Typical case is a bus with a fuel tank in front of the vehicle and engine including fuel feed pump in the rear. Length of the fuel suction pipe is about 10 meters where up to 0.4 bar pressure drop has been measured in laboratory cold tests.

Generally viscosity is not a limit for cold operability but in some cases it is worth for taking into account [7]. Also burner type auxiliary engine heaters may have quite narrow fuel suction pipes and low power feed pumps.

On the other hand fuel system designers have to take into account low viscosities since fuel temperature may be above 100°C in some parts of the fuel system during normal driving.

Cold Flow Additives

When diesel fuel is cooled down to temperatures below cloud point wax crystals begin to be formed and come out from the solution. They are platelet crystals which may have a size of more than one millimeter if the fuel is not treated with cold flow additives [3]. It is absolutely sure that this kind of crystals plugs also possible fuel screens and pre-filters in addition to the main filters. The size and shape of crystals can be modified to be smaller and three-dimensional by using CFPP improver additives. These crystals are less prone to attach themselves to each other and form agglomerates that restrict fuel flow [3], [9, page 433-]. However, the size of crystals is still too large to go through final fuel filters of vehicles.

In addition to the cold flow improver additives Wax Antisettling Additives (WASA) or wax dispersants can be used in order to further reduce the crystal size down to about 5 µm [3]. WASA additives are always used in association with CFPP additives. They slower the paraffin crystals settling rate to the bottom of fuel tanks when fuel is stored for a longer time at a temperature below cloud point. However, precipitation may take place in any case during a long storage below cloud point. If a vehicle is parked for some weeks cloud point should be below ambient temperature to be on a safe side. The same applies for above-ground storage tanks with slow fuel flow-through.

Regarding cold properties cloud point is the first fundamental issue to be achieved at an oil refinery by distilling, cracking and blending suitable middle distillate streams. When fuel has a desired cloud point, CFPP will be very near the cloud point or only a couple of degrees below that. As the second step cold flow improver additives are added reducing CFPP and also pour point to be some 10°C or even more below cloud point flow [9, page 437]. Additives have very limited if not any effect on cloud point. During the last decades final boiling points and aromatic contents of diesel fuels have been decreased because of reasons related to exhaust emissions. This has made choosing of appropriate cold flow additives even more challenging than it was earlier.

Solvents and Aftermarket Additives

During the last decades it was quite common to blend kerosene or gasoline into diesel fuel for enhancing cold operability. As a matter of fact 20 % gasoline or kerosene improved CFPP by some 5°C according to Neste Oil's measurements. However, today it is usually forbidden by automotive companies because of risks related to lubricity.

cetane number, vapor locks and cavitation. In addition to that even a tiny amount ($< 0.5\%$) of gasoline reduces flash point of diesel fuel to $< 55^{\circ}\text{C}$ which increases risk of fire and is illegal in many market areas. Oil companies can not either add kerosene at terminals or at refineries any more because sulfur content of aviation kerosene is usually too high and cetane number too low to be blended under the current diesel fuel specifications.

In principle it is possible to add cold flow improver additives into fuels afterwards and such kind of additives are sold for vehicle owners in small bottles. However, a common practice in the refineries is to add an optimum amount of additive which is optimized for the fuel's composition. In order to get good mixing fuel has to be warm enough or additive has to be diluted beforehand with a solvent. With an aftermarket additive there is a risk for problems because of over-dozing or temperature which is too low for a proper solubility.

So, the only way to produce good winter grade diesel fuels is to distill too heavy paraffins out or blend narrow distillation fractions which are suitable for diesel fuel. Also some special refinery processes like isomerization can be used for enhancing cold properties. Challenge of any blending is that the heaviest paraffins still exist in the blend and the higher cloud point product dominates. This can be seen from [figure 3](#) which shows that cloud point does not behave linearly in the blends. By other words, good cold properties can be produced only at oil refineries, not by any measures afterwards.

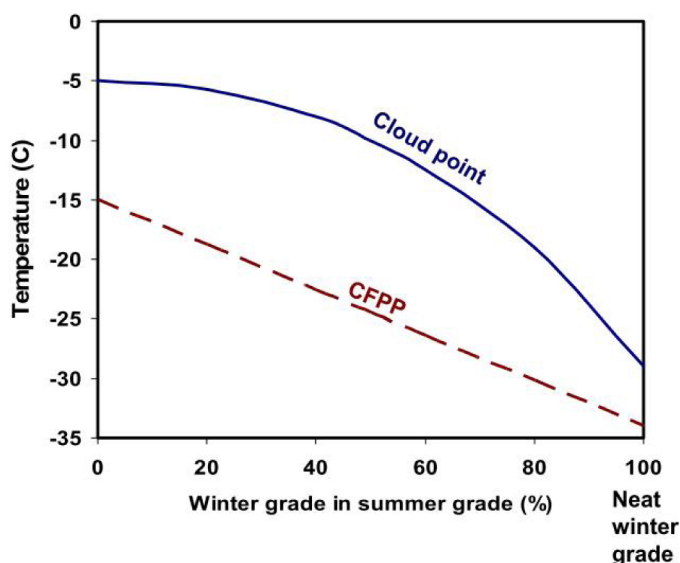


Figure 3. Blending behavior of cloud point and CFPP
(source Neste Oil measurements).

VEHICLE FUEL SYSTEMS IN COLD CONDITIONS

If ambient and fuel temperature in fuel tank is above fuel's cloud point and fuel is free from contaminants it goes through fuel filters without troubles. So, if cloud point is below ambient temperature it is an indicator for absolutely safe operability with high quality hydrocarbon type fuels which are free from water and impurities.

When a vehicle is started and driven at a temperature below fuel's cloud point fuel filter begins to pick up paraffin crystals inevitably. Sooner or later crystals cause pressure drop over the filter restricting fuel flow to the engine yielding to power loss and finally the engine stops. The smaller the crystals are or the more porous wax layer they form, the later filter plugs which is the benefit of cold flow additives. Also, the bigger filter surface area is, the later the filter plugs since there is more room for crystals to be picked up [9, page 467-].

For cold operability it is fundamental that during driving fuel temperature rises up to above fuel's cloud point and wax crystals begin to melt back to liquid so that driving is able to go on without problems. Cold flow improver additives give more time for the fuel system to warm up but they do not enable driving if fuel temperature keeps below cloud point at fuel filter long enough.

Some details of vehicle design have a clear effect on how soon fuel temperature warms up to above cloud point. Fuel filter can be located near the engine block in order to get radiation heat, it can be heated by electric heating element or heat exchanger connected to the coolant system [9, page 464-]. One possibility is to use fuel return flow coming from injection pump to warm up the filter.

There is no need to heat fuel to any high temperatures since some $10 - 20^{\circ}\text{C}$ above ambient temperature may be well enough to get fuel's temperature above cloud point when it goes into the filter. This, combined with the fact that specific heat ($\text{kJ/kg}^{\circ}\text{C}$) of fuels is quite low, means that quite reasonable heating powers are enough ($100 - 200\text{ W}$) [4].

[Figure 4](#) shows an example of cars with different fuel systems tested in a climate chamber. Cloud point of fuel was -22°C , CFPP -32°C , and it contained cold flow improver additive. Car with fuel filter in a warm location was started clearly below fuel's cloud point at -29°C . Pick up of paraffins by the fuel filter can be seen from the rising pressure drop over the filter. Fuel temperature at filter reached cloud point at 10 min after the start and paraffins began to melt when temperature increased further to a couple of degrees above cloud point. Then the increased pressure drop disappeared and driving was able to go on. When fuel filter was located in a cold place, the filter picked up paraffins until the car stopped after 30 minutes of driving although the test began at -26°C with the same test fuel [4].

The very beneficial effect of a coolant operated fuel heater is presented in [figure 5](#). The pressure drop over the filter was minimal although the test began at -34°C which was slightly below CFPP.