



Propulsion of 14,000 teu container vessels

MAN Energy Solutions
Future in the making

New Panamax

Modern two-stroke engine technology
for a modern vessel type

Future in the making

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In anticipation of the completion of the new Panama Canal, planned for 2014 and actually opened in 2016, the “New Panamax” type of container vessels has been a popular category since the early 2010s. New Panamax vessels offer easy access to the large market of North America as well as good flexibility, as the vessels offer adequate economy of scale to trade on many other routes.

Dimensions of the new Panama locks are shown in Table 1, along with maximum permissible vessel dimensions. Compared to the old Panama locks, larger margins between the vessel and lock walls are required as the vessels are moved into the new locks by tugs, instead of being pulled by locomotives running along the locks.

The maximum permissible breadth of a vessel passing the new Panama locks has been extended from the original limit of 49 m to 51.25 m in 2018. The permissible breadth of 51.25 m allows for 20 rows of containers, which results in a practical vessel breadth of approx. 50.7 to 51.0 m, compared to the 49 m limit that allowed for 19 rows of containers, and therefore resulted in a practical vessel breadth of approx. 48.2 to 48.5 m.

In the early 2000s the largest container vessels of the time were constructed with K98MC/K98ME/K98ME-C engines with nominal 97 rpm and 104 rpm respectively, as the propeller

demanded a high rpm figure due to the high design speeds of 24-26 knots.

During the 2000s container vessels grew in size. The cooling of the world economy in the late 2000s and the continuously increasing oil price resulted in a slowdown of the largest vessels.

The slowdown led to a design speed of approx. 22 knots for new ultra-large container vessels (ULCV) on the drawing board at the time. This came hand-in-hand with engines of a longer stroke and lower rpm, such as the super-long-stroke S-type engines and later the ultra-long-stroke G-type engines. Through improved engine performance and the application of larger propellers, significant savings were ensured.

Though more efficient options were available, the recent highs and lows of the freight market experienced at the beginning of the 2010's led to some hesitation amongst shipowners to

reduce the power capacity of New Panamax vessels, should the market turn. Therefore vessels of New Panamax dimensions delivered in the early 2010s maintained a high design speed of typically 24 to 25 knots, and the K98ME-C engine continued to be a popular choice for such vessels. It was not until 2012 that the K98ME-C engine was superseded by the S90ME-C in combination with a propeller of a larger diameter. This ensured significant savings for these New Panamax vessels as well.

This paper contains two case studies of a 14,000 teu New Panamax vessel with a design speed of 21.5 or 23.5 knots. These case studies will illustrate the economical and environmental benefits of New Panamax vessels applying the latest engine technology included in the G-type mark 10 engine designs, along with an increased propeller diameter. A comparison of the dimensions of the engines for New Panamax vessels of the past, present, and future are shown in Fig. 1.

Early New Panamax and other vessels with the popular K98 engine family (typically in the 6,500 teu to 11,500 teu range) can benefit from retrofit solutions described in the separate paper “8,500 teu container vessel optimisation”. Hereby more than 11% fuel savings can be achieved, which make the mid-size container vessels, previously part the Post Panamax segment, of interest as “New Panamax” vessels.

Dimensions

	Locks	Vessel, maximum dimensions
Length	427 m	366 m
Breadth	55 m	51.25 m
Draught	18.3 m	15.2 m
Height	-	57.9 m
teu	-	13-15,000

Table 1: Dimensions of new Panama Canal locks and New Panamax vessels

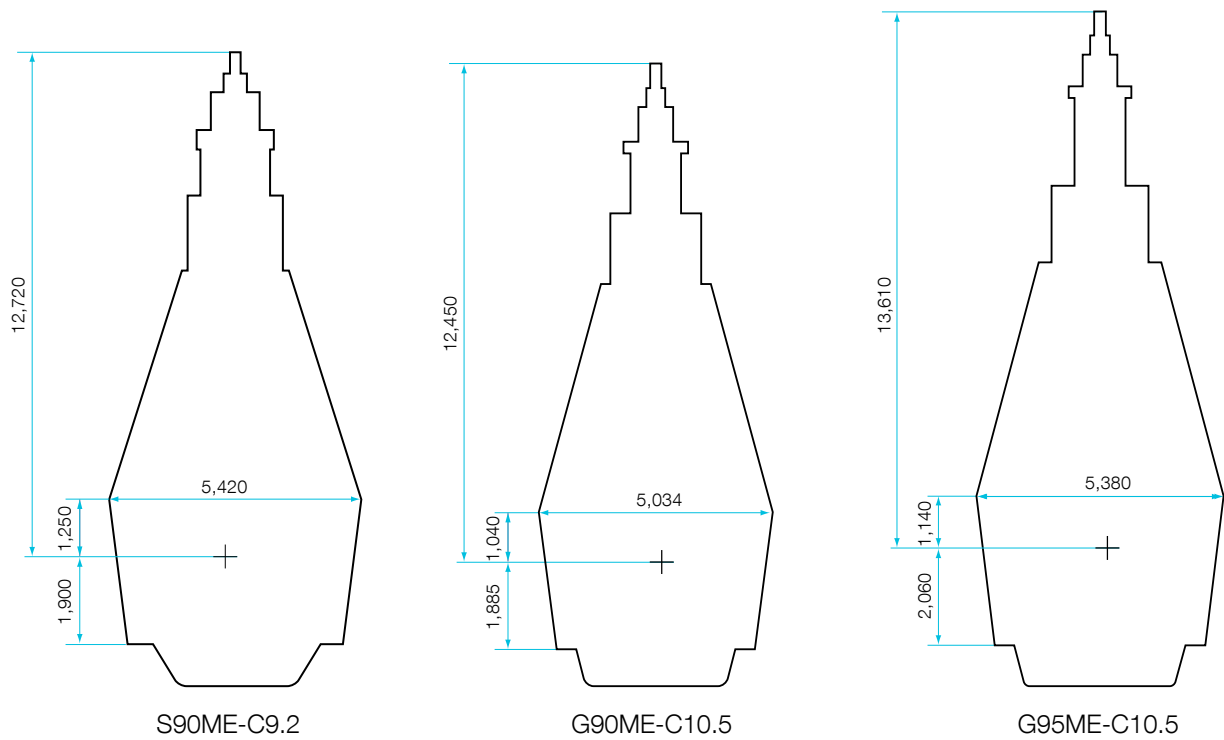


Fig. 1: Main dimensions of S90ME-C9.2, G90ME-C10.5, and G95ME-C10.5 engines, all measurements in mm

Energy efficiency, major propeller, and engine parameters for an example vessel

EEDI for container vessels

The Energy efficiency design index (EEDI) guidelines are a mandatory instrument adopted by the International Maritime Organization (IMO) that ensures compliance with international requirements on CO₂ emissions of new ships. The EEDI represents the amount of CO₂ in gram emitted when transporting one deadweight tonnage of cargo for one nautical mile:

$$\text{EEDI} \approx \frac{\text{CO}_2}{\text{Transport work}}$$

The EEDI is calculated on the basis of cargo capacity, propulsion power, vessel speed, specific fuel oil consumption (SFOC) and fuel type. However, certain correction factors are applicable, and reductions can be obtained by e.g. installing waste heat recovery systems (WHRS).

A reference index for a specific vessel type with an intended cargo capacity is calculated based on data from vessels built in the period 2000 to 2010. According to the EEDI guidelines implemented on 1 January 2013, the required EEDI for new vessels is reduced in three steps. This leads to a final EEDI reduction of 30% for a vessel built after 2025 compared to the reference value.

For a container vessel the reference index is calculated based on 100% utilisation of capacity (in dwt) as for all other vessel types. The attained EEDI, on the other hand, is calculated based on 70% capacity utilisation, with a reference speed in consistency with this loading of the vessel, at 75%

SMCR, with the hull in sea trial condition. The attained EEDI must not exceed the required EEDI.

There are a number of methods that can be applied to lower the EEDI value. By derating the engine, the specific fuel oil consumption (SFOC) is lowered as the mean effective pressure is reduced relative to the maximum (firing) pressure, which remains constant. Engine tuning methods such as exhaust gas bypass (EGB) and high-pressure tuning (HPT) can optimise the fuel curve at part- and low-load operation, thus reducing SFOC at 75% load, the EEDI reference value. Part-load tuning will typically provide the lowest SFOC at the EEDI reference value. In the case studies in this paper, low-load optimisation of the main engine is applied to reflect the slow steaming of modern container vessels.

EcoEGR is a special option available for engines with EGR. Through activation of the EGR system also when in Tier II mode, it is possible to optimise the combustion parameters for optimum efficiency. The EGR plant reduces the emission of NO_x and ensures Tier II compliance. This allows the fuel consumption to be lowered significantly in Tier II mode, as illustrated by the inclusion of an engine with EcoEGR in each of the case studies.

The power installed is also a parameter that can be reduced to achieve a lower EEDI. This can be achieved by either lowering the vessel speed, by improving the hull design to minimise resistance, or by optimising the propeller design, e.g. through the

application of a Kappel propeller. Additionally, various energy saving devices, typically altering the flow fore or aft of the propeller, can be applied.

Installation of green technologies, like WHRS or changing fuel to e.g. liquid natural gas (LNG) or liquefied petroleum gas (LPG), methanol, etc. will also lower the EEDI value.

For further information on the calculation of EEDI, and the reduction hereof and other environmental regulations, see Chapter 4 of the separate paper “Basic principles of ship propulsion”.

Major propeller and engine parameters

In general, the larger the propeller diameter, the higher the propeller efficiency, and the lower the optimum propeller speed referring to an optimum ratio of the propeller pitch and propeller diameter.

A lower number of propeller blades, for example going from 6 to 5 blades, if possible, would mean an approximately 10% higher optimum propeller speed, and a slight increase in the propeller efficiency. When increasing the propeller pitch for a given propeller diameter with optimum pitch/diameter ratio, the corresponding propeller speed may be reduced. The efficiency will also be slightly reduced, of course depending on the extent to which the pitch is changed. The same is valid for a reduced pitch, but here the propeller speed may increase.

The efficiency of a two-stroke main

engine depends particularly on the ratio of the maximum (firing) pressure and the mean effective pressure. The higher the ratio, the higher the engine efficiency, and the lower the SFOC.

Furthermore, the higher the stroke/bore ratio of a uniflow scavenging two-stroke engine, the higher the engine efficiency, as the scavenging process improves

with a higher stroke/bore ratio. This means that the ultra-long-stroke G-type engines by design have a higher efficiency than the previous K- and S-type engines applied on container vessels.

Through the two case studies, the influence on fuel consumption of applying a G-type engine instead of the

traditional S90ME-C9.2 is illustrated, along with the effect of increased propeller diameter.

The layout diagram of the S90ME-C9.2 is plotted in Figs. 2 & 3 for the two cases of 23.5 and 21.5 knots, respectively, along with the modern alternatives, the G90ME-C10.5 and G95ME-C10.5 designs.

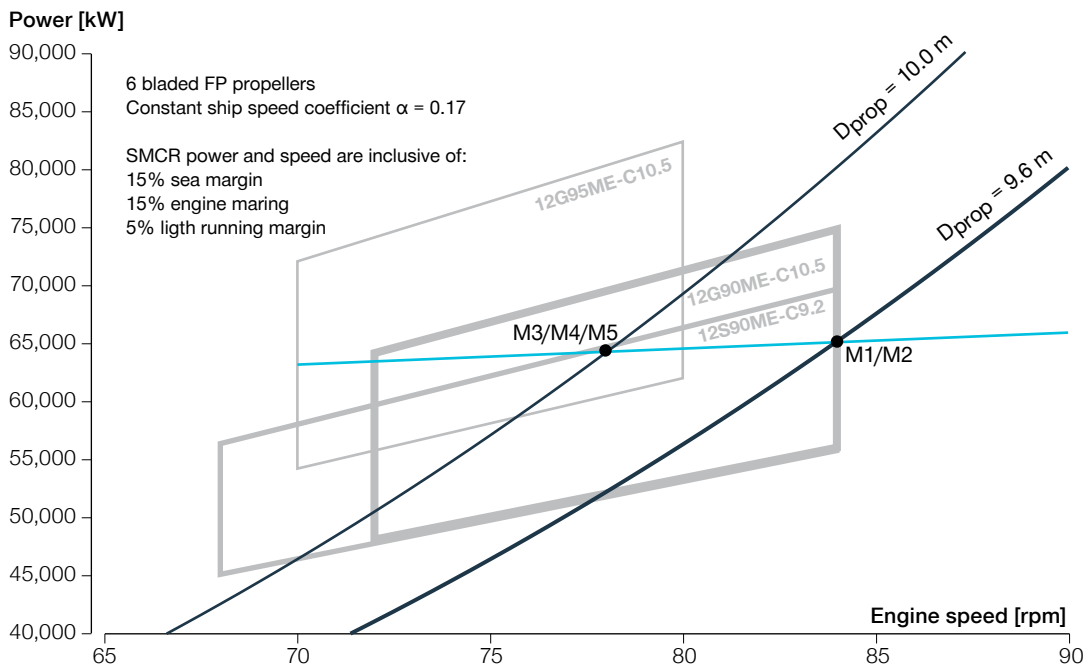


Fig. 2: Engine layout diagrams and propeller curves for a 6-bladed propeller with 5% light running margin, $V_{design} = 23.5$ knots

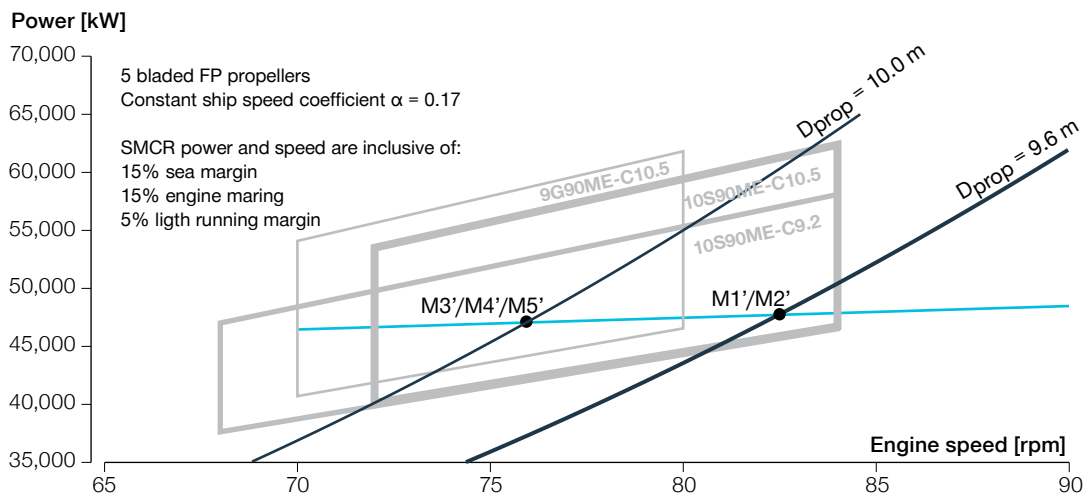


Fig. 3: Engine layout diagrams and propeller curves for a 5-bladed propeller with 5% light running margin, $V_{design} = 21.5$ knots

14,000 teu container vessel example

For a 14,000 teu New Panamax vessel used as an example, the following case studies illustrates the potential for reducing fuel consumption by increasing the propeller diameter and applying G-type engines as main engine.

Based on the vessel particulars assumed in Table 2, power prediction calculations (Holtrop & Mennen's method) have been performed for different design speeds and propeller diameters. The corresponding SMCR power and rpm, point M, for propulsion of the container vessel, has been found including the sea, engine, and light running margin, see Figs. 2 & 3.

For both cases a propeller diameter of 9.6 and 10.0 m has been investigated,

with a 5-bladed design applied for the 21.5 knots case and 6-laded design for the 23.5 knots case.

The propeller diameter change applied in both case-studies corresponds approximately to a constant ship speed factor, α , of:

$$\alpha = 0.17 \quad [P_{M2} = P_{M1} \times (n_2/n_1)^\alpha]$$

where P is the propulsion power and n is the rotational speed.

For the *same propeller diameter*, when going from 6 to 5 blades, the optimum propeller speed is increased and the propulsion power needed is slightly increased.

Referring to the two design speeds of 23.5 knots and 21.5 knots, potential main engine types and pertaining

layout diagrams and SMCR points have been plotted in Figs. 2 & 3 respectively. The main engine operating costs have been calculated and will be described in detail for both cases in the following sections.

It should be noted that the design speed stated refers to the design draught and to a normal continuous rating (NCR) = 85% SMCR including 15% sea margin. If based on calm weather, i.e. without a sea margin, the obtainable vessel speed at NCR = 85% SMCR will be about 0.9 to 1.0 knots higher.

If based on 75% SMCR, 70% of maximum dwt, calm water, and the hull in sea trial condition, as applied for calculation of the EEDI for container vessels, the vessel speed will be about 0.1 to 0.2 knots higher than the design speed at NCR.

14,000 teu container vessel

Deadweight, max	dwt	150,000
Scantling draught	m	15.8
Design draught	m	14.5
Length overall	m	368.0
Length between pp	m	352.0
Breadth	m	51.0
Sea margin	%	15
Engine margin	%	15
Light running margin	%	5
Design ship speed	kn	21.5 / 23.5
Type of propeller		FPP
No. of propeller blades		5 / 6
Propeller diameter	m	9.6 - 10.0

Table 2: Vessel particulars for a typical New Panamax vessel

Main engine operating costs **23.5 knots**

Main engine examples for $V_{\text{design}} = 23.5$ knots

Engine	SMCR point	NCR	D_{prop}
12S90ME-C9.2	M1: 65,200 kW, 84 rpm	N1: 55,420 kW	9.6 m
12G90ME-C10.5	M2: 65,200 kW, 84 rpm	N2: 55,420 kW	9.6 m
12G90ME-C10.5	M3: 64,235 kW, 78 rpm	N3: 54,600 kW	10.0 m
12G95ME-C10.5	M4: 64,235 kW, 78 rpm	N4: 54,600 kW	10.0 m
12G95ME-C10.5-EcoEGR	M5: 64,235 kW, 78 rpm	N5: 54,600 kW	10.0 m

Table 3: Calculated main engine examples for 23.5 knots, the only difference between M4 and M5 is the inclusion of EcoEGR

Fuel consumption at NCR

The power required at NCR = 85% SMCR for propelling the container vessel at the relatively high speed of 23.5 knots, depending on propeller diameter, is illustrated in Fig. 4. Here it is illustrated that N3 and N4 have a 1.5% lower power demand due to the propeller diameter of $D_{\text{prop}} = 10.0$ m compared to the smaller diameter of $D_{\text{prop}} = 9.6$ m applied for N1 and N2.

A propeller diameter of 10.0 m is not only interesting due to the reduced power required to propel the ship, but also due to the lower optimum propeller rpm. With the lower rpm, the SMCR point falls within the layout diagram of the larger G95ME-C10.5 engine, which ensures significant savings.

Fig. 5 shows the influence on the main engine efficiency, indicated by the

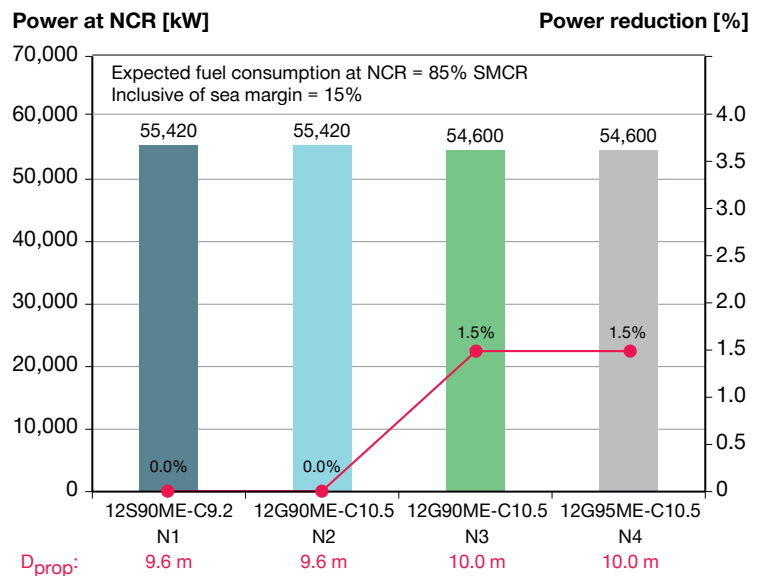


Fig. 4: Expected propulsion power demand at NCR = 85% SMCR for $V_{\text{design}} = 23.5$ knots

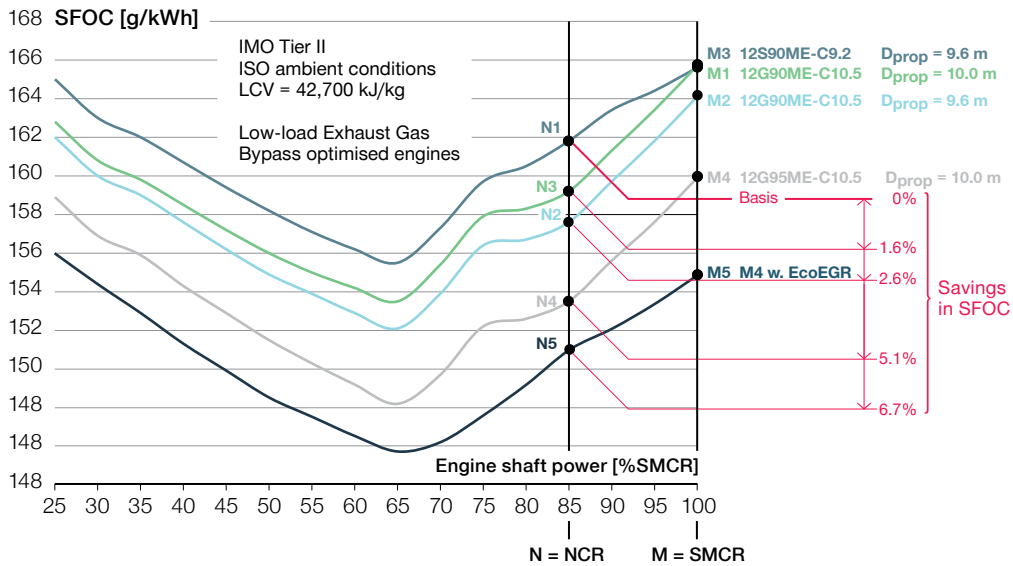


Fig. 5: SFOC for V_{design} = 23.5 knots as of 2018. For reference, use the online calculation tool CEAS available on our home page

specific fuel oil consumption (SFOC) for the four cases. Several interesting results beside the significant reductions ensured by applying EcoEGR can be highlighted:

At N3 = 85% of M3, the 12G90ME-C10.5 has an SFOC of 159.2 g/kWh. This is remarkable, as N2 for the same 12G90ME-C10.5 engine, but with a smaller propeller, has a lower SFOC of 157.6 g/kWh. This is explained by the position of the SMCR point within the engine layout diagrams depicted on Fig. 2 for the 23.5 knots case. Fig. 2 shows that M2 is located relatively lower within the engine layout diagram than M3, which implies that M2 is more derated than M3.

As N4, the larger 12G95ME-C10.5 stands out with a very low SFOC of 153.5 g/kWh at 85% load, which can be reduced even further to 151.0 g/kWh if EcoEGR is applied.

If in an actual case the optimum propeller rpm falls slightly outside the layout diagram of this engine, it would be worth investigating the potential of increasing the pitch in order to lower the rpm of the propeller. This will decrease the efficiency of the propeller, but may be a sensible sacrifice for a larger increase in engine efficiency.

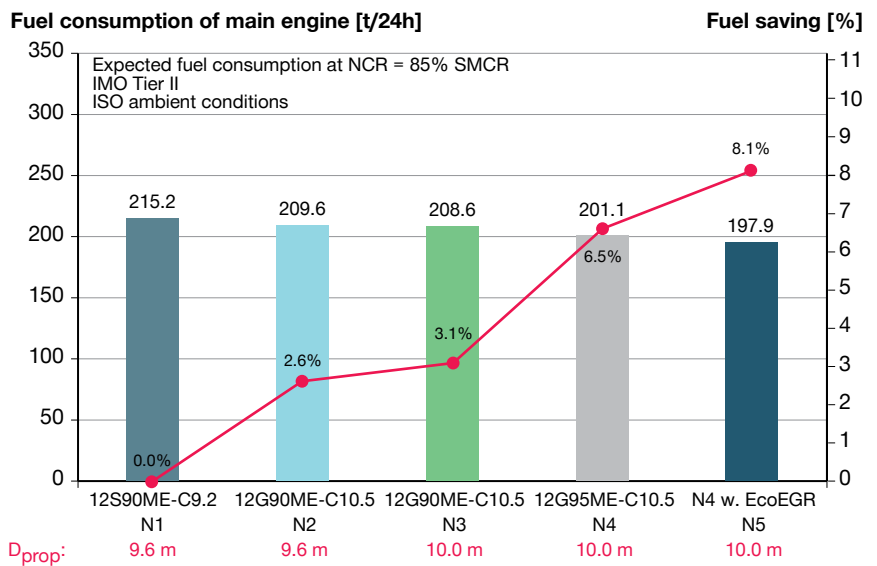


Fig. 6: Expected daily fuel consumption at NCR for V_{design} = 23.5 knots

When multiplying the propulsion power demand at N (Fig. 4) with the SFOC (Fig. 5), the daily fuel consumption is found, which is shown in Fig. 6. The 12G95ME-C10.5-EcoEGR engine results in the lowest daily consumption, as it has the lowest SFOC and largest propeller diameter.

Despite the fact that the SFOC of N3 is higher than the SFOC of N2, the daily fuel consumption at 85% SMCR of N3

will still be lower than N2, due to the increased propeller diameter.

This illustrates that in this case it can be beneficial to sacrifice some engine efficiency for a larger increase in propeller efficiency by increasing the propeller diameter. The ship designer must evaluate these options to ensure the best design, depending on the priorities of the project.

EEDI

The reference and the actual EEDI figures have been calculated for a low-load optimised engine including a 6% tolerance on the SFOC and without any consideration to a shaft generator, WHRS or energy saving devices. As such, the calculated EEDI is considered to be conservative, see Fig. 7.

As can be seen in all four cases, the actual EEDI figures are lower than the index required after the implementation of EEDI phase 3 (30% reduction compared to the reference line) in 2025.

$$EEDI_{ref-containerer} = 174.22 \times dwt^{-0.201}$$

This is partly an effect of the decrease in design speed since the 2000s (on which the reference value is based) and the significant savings offered by the development that have happened within propulsion machinery for container vessels. The EEDI reference speed V_{ref} is calculated by Holtrop & Mennen’s method as previously described.

Operating costs

Whereas the previous comparisons of engine fuel performance are based on a constant engine load of 85% (NCR), the yearly operational costs of the engine greatly depends on the engine’s load profile.

Container carriers typically sail in scheduled traffic with trans-oceanic crossings and hereafter port calls along the coast of a continent. This gives a rather predictable load profile. Maintaining the schedule is important in order to get to the right place at quay with allocated resources, why some operation at high loads are expected in order to catch up delays or counter harsh weather.

An example of a load profile for a New Panamax vessel, see Fig. 8, is applied to calculate the total main engine operating costs per year, including lubricating oil costs etc., assuming 280 days/year at sea (≈25% in port).

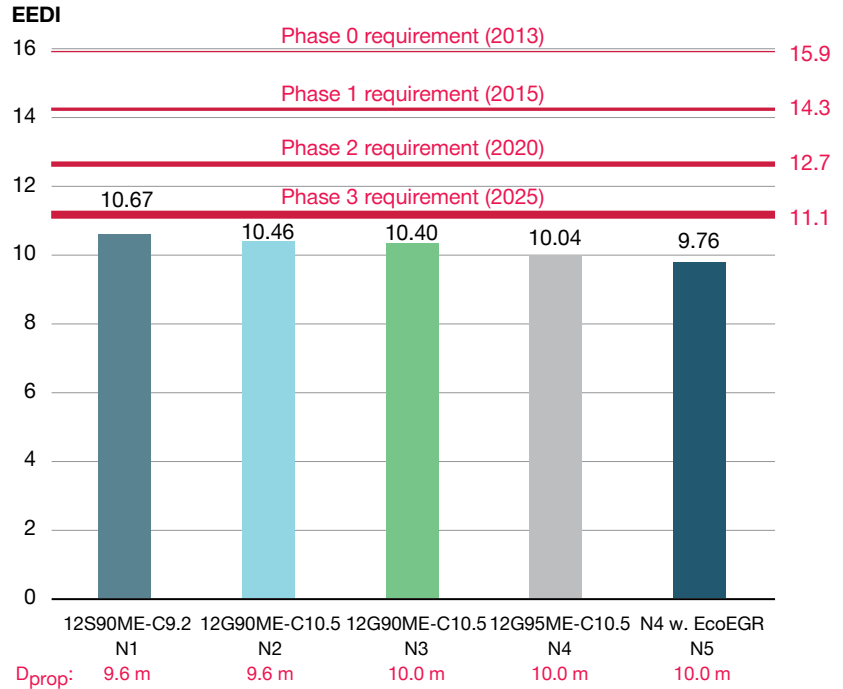


Fig. 7: Required and attained EEDI for $V_{design} = 23.5$ knots, 70% capacity and 75% SMCR. $V_{ref} = 23.6$ knots

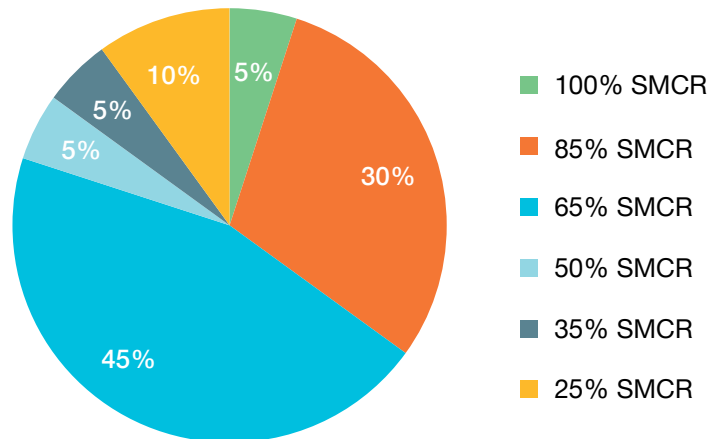


Fig. 8: Load profile [%running hours]

For these calculations is a fuel price of 450 USD/t and a lubricating oil price of 2,000 USD/t assumed. A price of 200 USD/t is assumed for the NaOH (in a 50% solution) required to operate the EGR, as well as a price for handling the discharged sludge of 100 USD/t is assumed. The results for the main engine operating costs per year are shown in Fig. 9.

The operating costs in net present value (NPV), using the 12S90ME-C9.2 with a propeller diameter of 9.6 m (M1) as reference, indicates a significant NPV saving for the G-type engines, as illustrated in Fig. 10.

After 10 years in operation, the saving for M2, a 12G90ME-C10.5 with the same propeller diameter as M1, would amount to 4.0 million USD. For M3, a 12G90ME-C10.5 with a larger propeller diameter than M2, the saving after 10 years would be about 5.0 million USD.

Significantly larger savings can be achieved with the 12G95ME-C10.5. For the standard version, a saving of 10.9 million USD is achieved after 10 years.

If EcoEGR is applied, a saving of 12.3 million USD can be achieved. This saving is relatively smaller than the resulting fuel saving of applying EcoEGR (see Fig. 5 & 6), as the cost of operating the EcoEGR has been included.

If more expensive fuels, e.g. low sulphur fuels, are used instead of HFO, as applied in this example, the economic savings of EcoEGR will be significantly larger: The operating costs of EcoEGR and the relative fuel saving achieved are independent of the sulphur content of the fuel.

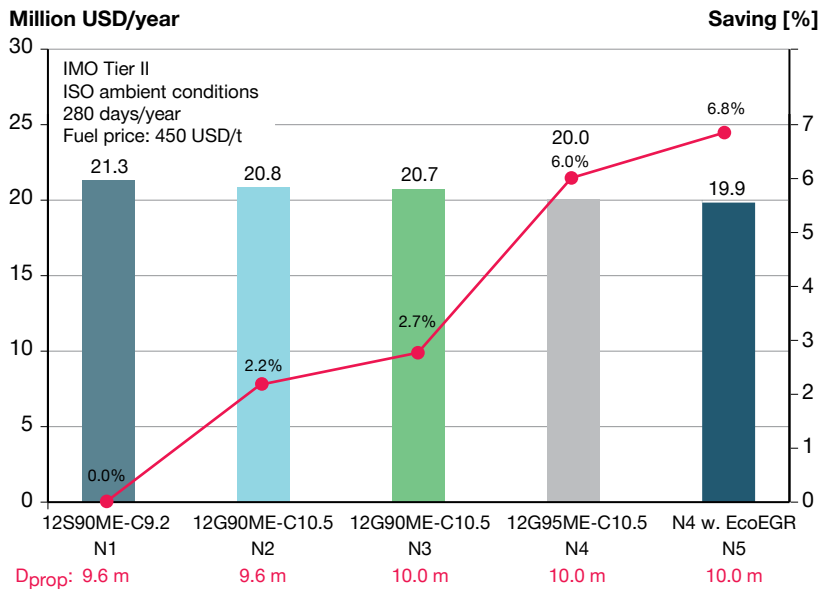


Fig. 9: Total annual main engine operating costs including fuel, cylinder, system lubricating oil, and if applicable EcoEGR running costs for $V_{design} = 23.5$ knots

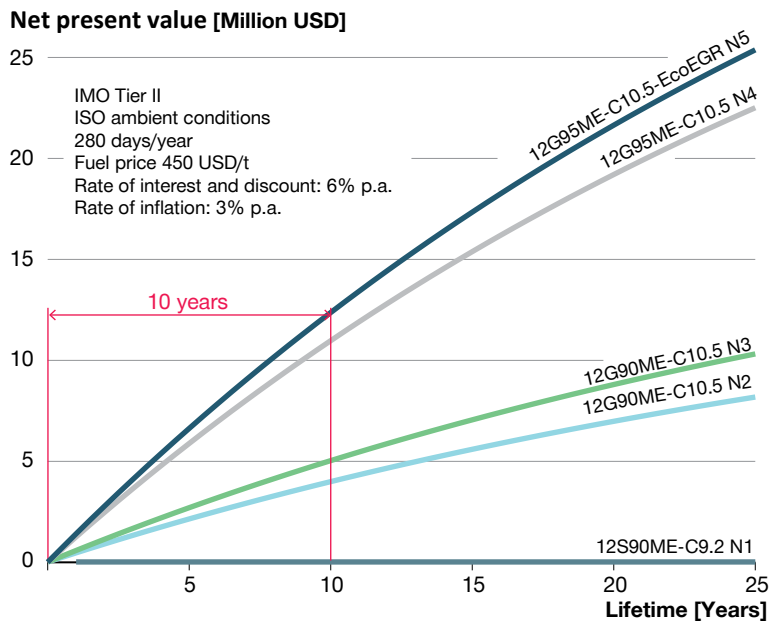


Fig. 10: Savings in main engine operating costs (NPV) for $V_{design} = 23.5$ knots

Main engine operating costs 21.5 knots

Main engine examples for $V_{design} = 21.5$ knots

Engine	SMCR point	NCR	D_{prop}
10S90ME-C9.2	M1': 47,750 kW, 82.5 rpm	N1': 40,588 kW	9.6 m
10G90ME-C10.5	M2': 47,750 kW, 82.5 rpm	N2': 40,588 kW	9.6 m
10G90ME-C10.5	M3': 47,160 kW, 76 rpm	N3': 40,086 kW	10.0 m
9G95ME-C10.5	M4': 47,160 kW, 76 rpm	N4': 40,086 kW	10.0 m
9G95ME-C10.5-EcoEGR	M5': 47,160 kW, 76 rpm	N5': 40,086 kW	10.0 m

Table 4: Calculated main engine examples for $V_{design} = 21.5$ knots, the only difference between M4' and M5' is the inclusion of EcoEGR

Fuel consumption

The power required at NCR = 85% SMCR for propelling the container vessel at the lower design speed of 21.5 knots is illustrated on Fig. 11. Here it is illustrated that N3 and N4 have a 1.2% lower power demand due to the propeller diameter of $D_{prop} = 10.0$ m compared to $D_{prop} = 9.6$ m applied for N1 and N2.

Again, a propeller diameter of 10.0 m allows the application of the larger G95ME-C10.5 engine type. As seen on the engine layout diagram plotted on Fig. 3, the SMCR point is close to the lower limit of the layout diagram for the 9 cylinder version of this engine type. Therefore, a 9 cylinder version is employed, and not a 10 cylinder version as for the G90 engines in the comparison. The reduced cylinder number will reduce lubricating oil consumption and maintenance costs as well.

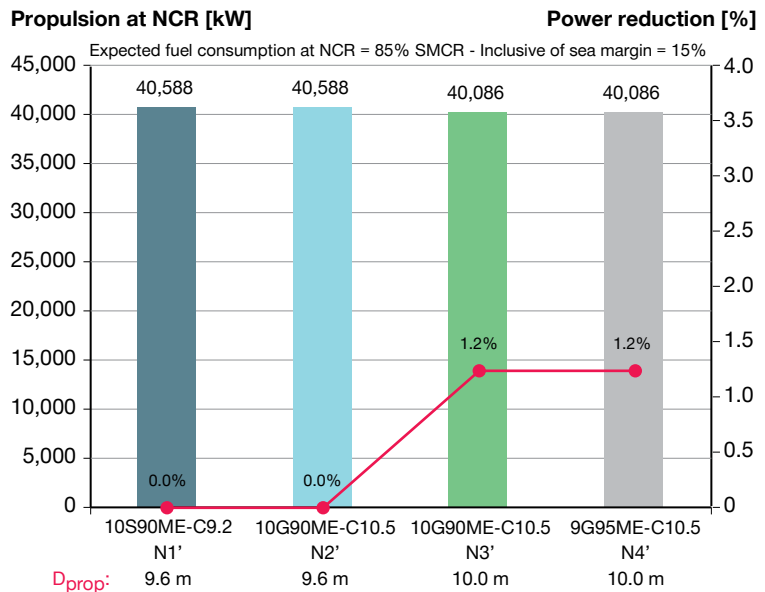


Fig. 11: Expected propulsion power demand at NCR = 85% SMCR for $V_{design} = 21.5$ knots

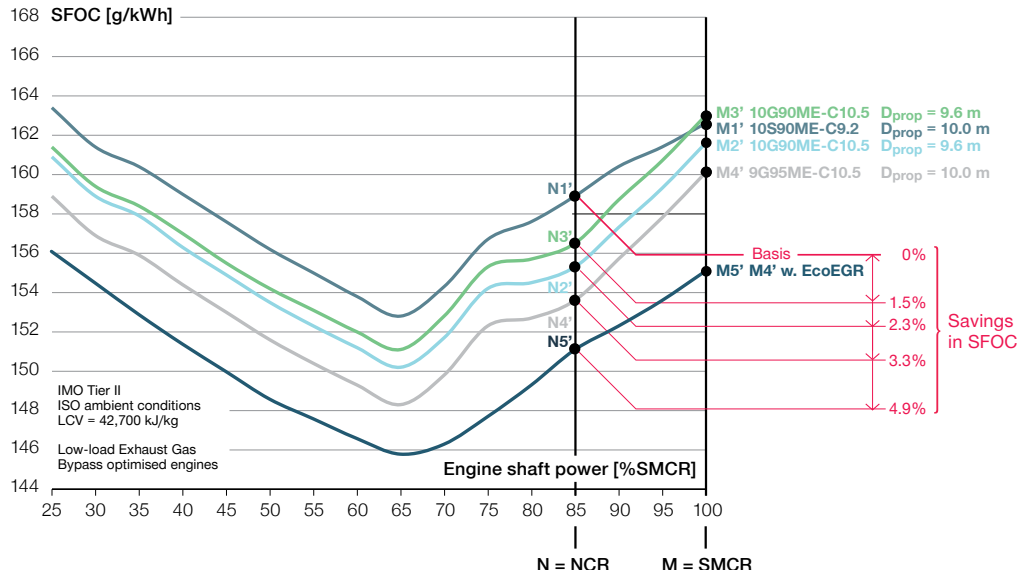


Fig. 12: SFOC for $V_{design} = 21.5$ knots as of 2018. For reference, use the online calculation tool CEAS available on our home page

Fig. 12 shows the influence on the main engine efficiency, indicated by the SFOC. Again, the effect of the fact that N2' is more derated than N3' can be seen, but the G95ME-C10.5 (N4') excels with the lowest SFOC, reaching only 153.6 g/kWh at 85% SMCR and even 151.1 g/kWh if EcoEGR is applied.

When multiplying the propulsion power demand at N (Fig. 11) with the SFOC (Fig. 12), the daily fuel consumption is found and shown in Fig. 13. The 9G95ME-C10.5 engine results in the lowest daily consumption, as it has the lowest SFOC and largest propeller diameter, as well as the lowest lubricating oil consumption.

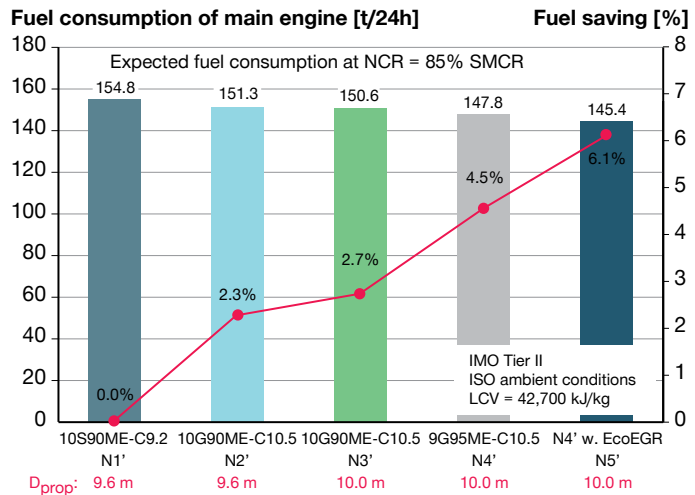


Fig. 13: Expected daily fuel consumption at NCR for $V_{design} = 21.5$ knots

EEDI

The reference and the actual EEDI figures have been calculated for a low-load optimised engine including a 6% tolerance on SFOC and without any consideration to a shaft generator, WHRS or energy saving devices. As such, the calculated EEDI is considered to be conservative, see Fig. 14.

When comparing to the EEDI of the 23.5 knots case, see Fig. 7, it is clear that a speed reduction greatly influences the EEDI. On average, the attained EEDI is reduced by a value of approximately 2. Further reductions can be achieved by considering some of the above-mentioned omissions and further speed reductions.

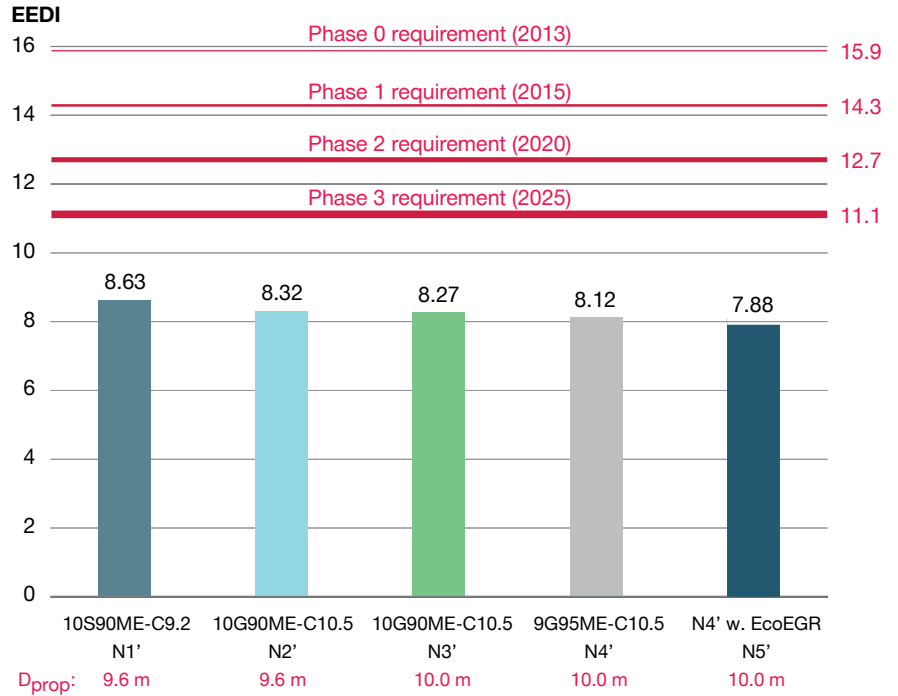


Fig. 14: Required and attained EEDI for $V_{design} = 21.5$ knots, 70% capacity and 75% SMCR. $V_{ref} = 21.7$ knots

Operating costs

Whereas the previous comparisons of engine fuel performance are based on a constant engine load of 85% (NCR), the yearly operational costs of the engine greatly depend on the engine's load profile, as already depicted in Fig. 8. For the calculations, 280 days/year at sea ($\approx 25\%$ in port) as well as a fuel price of 450 USD/t and a lubricating oil price of 2,000 USD/t are assumed along with 200 USD/t for the NaOH (in a 50% solution) and 100 USD/t for sludge discharge for the EcoEGR. The results are shown in Figs. 15 & 16.

As the actual fuel oil consumption is approximately 25% lower for the reduced design speed of the second case, the absolute savings are smaller than for the 23.5 knots case. Still, the G-type engine in combination with a larger propeller provides substantial savings compared to the 10S90ME-C9.2 engine. Savings that can be further enhanced by the application of EcoEGR.

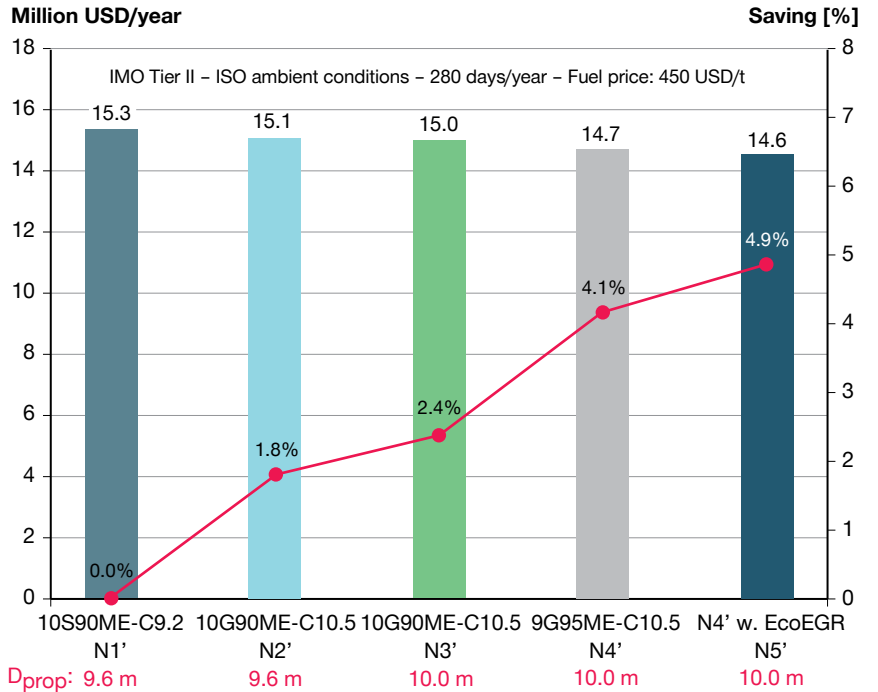


Fig. 15: Total annual main engine operating costs including fuel, cylinder, system lubricating oil, and if applicable EcoEGR running costs for $V_{design} = 21.5$ knots

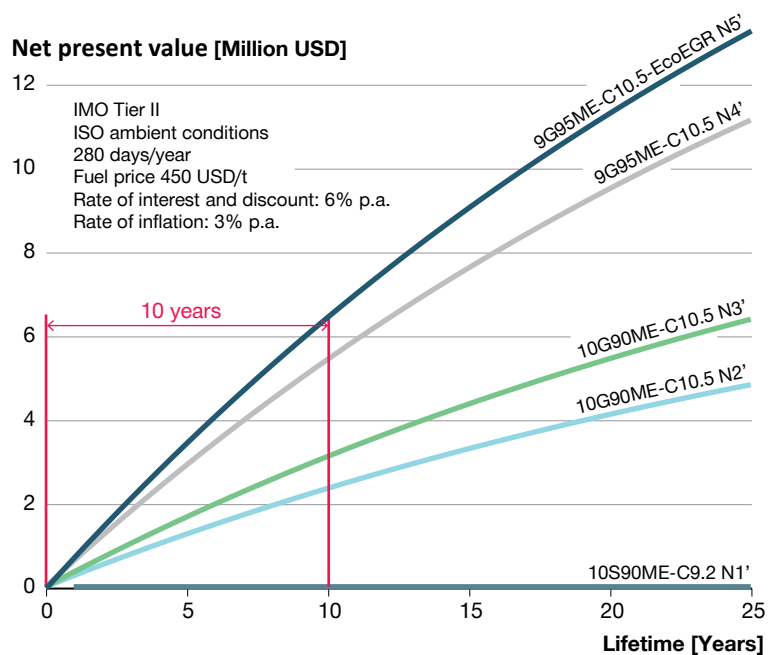


Fig. 16: Savings in main engine operating costs (NPV) for $V_{design} = 21.5$ knots

Summary

The ultra-long-stroke G-type engines have made their way into the container carrier market though the increase in propeller diameter and the lower design speed, following the current efficiency optimisation trends. Compared to existing main engines applied so far, e.g. the S90ME-C9.2, the G95ME-C10.5 in combination with a large propeller diameter offers a fuel saving of more than 6% and even more than 8% if EcoEGR is applied.

Modern New Panamax vessels with a fuel efficient G-type engine as well as modern ultra large container vessels fulfil EEDI phase 3 requirements (30% reduction) without calling for further initiatives. However, both from an

environmental and economical point of view, this does not mean that the application of various fuel saving measures are irrelevant.

Modern container vessels carry a large number of reefer containers, and have a large electrical consumption at sea. Therefore, the inclusion of a power take out/shaft generator on the main engine can be sensible, as the main engine can produce electric power at a lower SFOC than the auxiliary engines on board. Waste heat recovery systems can also contribute with a significant part of the electrical consumption at sea, and hereby increase the overall efficiency of the vessel.

Furthermore, various energy saving devices can be considered along with a high-efficiency Kappel propeller. Such high-efficiency propellers become increasingly relevant as a measure to increase propeller efficiency, as the diameter of propellers on container carriers approach a practical limit.

The broad power and speed range offered by MAN B&W engines ensures that an optimum match between engine and hull always can be achieved, for low as well as high vessel design speeds of New Panamax container vessels.

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