CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 493

Upgrading the MAN 32/40 engine with the new TCF20 turbocharger

Turbochargers & Air/Exhaust Management

Martin Kern, MAN Energy Solutions

Matthias Müller, MAN Energy Solutions
Maxim Epp, MAN Energy Solutions

ABSTRACT

New turbocharger developments will make a significant contribution to achieving emission reduction goals, in alignment with MAN Energy Solutions' strategy to reduce CO2 emissions by 10% before 2030. Innovative turbochargers offer potential for engine optimization and enable improvements for operation with alternative fuels.

MAN's new TCF turbocharger series was designed for very high specific flow, wide compressor maps, and high efficiency. The key components include MAN's high-flow radial compressor wheel in combination with a newly developed high-flow radial turbine. Its efficiency characteristics can be adjusted across a wide range, using different rotor-stator combinations, while maintaining consistently high efficiency levels throughout the entire volume flow range. The TCF has successfully passed comprehensive validation through a turbocharger test campaign. Furthermore, the TCF has already demonstrated significant performance benefits on a test engine, paving the way for potential engine upgrades. This paper will focus on the upgrade procedure and method, presenting results from the thermodynamic test program conducted on both the turbocharger test rig and on a test engine.

In both the 4-stroke and 2-stroke markets, the TCF turbocharger series offers versatile application options for new engine developments using conventional and future fuels, as well as for retrofit upgrades. For the latter option, casing variants are available with connection dimensions compatible with existing turbochargers. The TCF's very high specific volume flow can lead to smaller turbocharger frame sizes for certain cylinder numbers, simultaneously increasing turbocharger efficiency and optimizing load characteristics. Additionally, the TCF has downsizing potential as a low-pressure stage for 2-stage systems, where high specific flow is crucial.

TCF's first applied showcase is the successful MAN L+V32/40 engine, which has more than 4,000 units in operation. Data is drawn from an extensive test campaign involving the TCF20 frame size on the 7L32/40CD engine with 3500 kW. Engine tests confirm significantly reduced fuel consumption within the relevant operational range for marine applications, while also simplifying module complexity by using a single turbocharger frame size across all engine cylinder numbers.

1 INTRODUCTION

The maritime industry, a cornerstone of global trade, is undergoing a significant transformation driven by the urgent need to reduce greenhouse gas (GHG) emissions.

The International Maritime Organization (IMO) has defined the goal of achieving net-zero by 2050. Interim objectives are to reduce GHG emissions by at least 20% by 2030 and 70% by 2040 [1].

To realize these targets, the IMO has introduced instruments including the Carbon Intensity Indicator (CII) in November 2022 and the Energy Efficiency Existing Ship Index (EEXI) in January 2023. These instruments join the Energy Efficiency Design Index (EEDI) which has been in effect since 2013. These indicators are part of the IMO's broader strategy to cut greenhouse gas emissions and promote more sustainable shipping practices.

The CII measures a ship's carbon intensity by calculating the amount of CO_2 emissions per transported cargo ton and per nautical mile travelled and is valid for bigger vessels of 5000 gross tons and above (cargo ships, RoRo etc.). This indicator allows for the assessment and comparison of a ship's operational efficiency. A lower CII value indicates higher efficiency and lower emissions. The IMO has set targets for gradually reducing CII values by 2030 to minimize the environmental footprint of shipping.

The EEXI evaluates the technical efficiency of existing ships. It takes into account various factors such as ship type, ship size, and installed engine power to calculate an efficiency index. The EEXI is particularly important for older ships of more than 400 gross tons (e.g. coastal cargo ships, fishing trawlers and passenger ferries) that may not meet the latest environmental standards. By introducing the EEXI, these ships are expected to be retrofitted or adjusted to improve their energy efficiency and reduce emissions.

The EEDI is similar to the EEXI but applies to new ships. It measures the energy efficiency of a ship's design by considering the amount of CO_2 emissions per ton-mile. The EEDI sets mandatory energy efficiency standards for new ships, ensuring that they are built to be more energy-efficient and environmentally friendly. The EEDI is part of the IMO's efforts to ensure that new ships contribute to the reduction of greenhouse gas emissions from the outset.

All three indicators, CII, EEXI, and EEDI, are part of a comprehensive approach to promoting decarbonization in the shipping industry. They complement each other by assessing and improving both the operational and technical efficiency of ships, as well as ensuring that new ships, engines and components like turbocharger are designed with energy efficiency in mind. Implementing these measures, however, requires significant investments and technological innovations.

This is where the new TCF turbocharger series, developed by MAN Energy Solutions comes into play. MAN Energy Solutions and its turbocharger brand PBST, a leading provider of turbocharging and exhaust gas treatment systems, has developed this new turbocharger to further enhance the energy efficiency of engines. By integrating the new turbocharger into existing ship propulsion systems, shipowners can better meet the requirements of the EEXI and CII, while new ships designed to meet EEDI standards can also benefit from this technology. The turbocharger is one of the most cost-effective leverages for improving energy efficiency while contributing to global climate goals. Figure 1 shows the main systems with potential to improve these indices through retrofits. In most cases, modification of the main and auxiliary engines also results in a turbocharger upgrade. The combination of CII, EEXI, EEDI, and innovative technologies like the new MAN Energy Solutions turbocharger represent a significant step towards a more sustainable and environmentally friendly shipping industry.

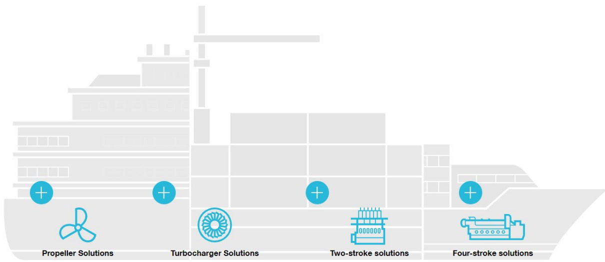

Figure 1: Optimization potentials to reduce GHG.

This paper describes how the newly developed TCF turbocharger series can improve the carbon footprint, the propulsive or electric and economic performance of an engine based on the first use case, the Efficiency Package of the 32/40CD.

2 TCF DEVELOPMENT TARGETS

MAN Energy Solutions (MAN ES) strives to cover a wide range of the Marine and Power market segment with its products. Therefore, the turbocharger portfolio also needs to be versatile.

2.1 Improving MAN's turbocharger portfolio with new radial turbochargers

In the demanding 2-stroke market, MAN's TCT series is a well-established product that demonstrates its competitiveness every day. Especially in combination with the solutions for exhaust gas recirculation (EGR), the EGR-Blower ETB40, or the SCR-HP series for selective catalytic reduction (SCR), additional value can be generated for the customer [2].

With the TCR small radial turbocharger series, MAN ES is able to equip high-speed and medium-speed engines with a high-performance turbocharger. 1-stage and 2-stage solutions are available for a variety of different engines and applications.

The wide 4-stroke market can only be covered by a range of turbocharging solutions. The 2-stage ECOCHARGE system focuses on large medium-speed engines. The TCX series provides a state-of-the-art high-pressure stage (HP stage), whereas the TCT has proven to be a very effective low-pressure stage (LP stage). Although the main market is that for bigger engines, MAN Energy Solutions provides 2-stage solutions for a wide range of engine performance levels for several customers.

As shown in Figure 2, the new TCP and TCF series complete and extend the existing turbocharger portfolio across all market segments, addressing upcoming developments in engine technology. The TCP series anticipates future requirements for various applications and fuels with its performance capabilities. In contrast, the TCF turbochargers additionally focus on optimizing existing engines by pushing the limits to the maximum and generating higher flexibility.

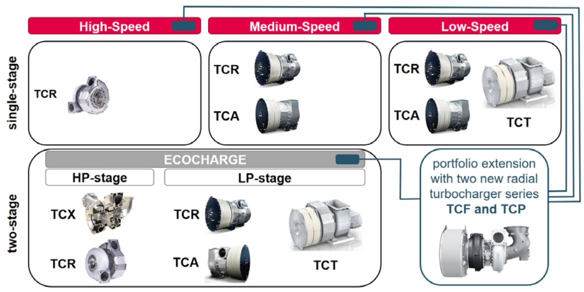

Figure 2: MAN ES turbocharger portfolio overview.

Both new radial turbocharger series offer a modular system for each frame size, providing wide variability in compressor and turbine configurations to optimize the turbochargers for various engine needs.

The TCP and TCF series each consist of 7 frame sizes. During the concept phase of the development process, it was decided to modify the frame size design in contrast to TCR to maintain a high performance levels across the entire application range. This also led to the introduction of an additional new frame size, TCP/TCF19.

The casings for all the turbocharger frame sizes were optimized for thermodynamic and mechanical performance, resulting in changes to the connecting dimensions compared to the TCR series. However, to facilitate easy engine installation and retrofit capability, the connection dimensions of specific frame sizes have been designed for plug-and-play installation.

2.2 TCF applications

The TCF is designed as a multi-purpose turbocharger prepared to accommodate all currently considered alternative fuels in the future. A pillar of the development is the high efficiency target for low-speed engines. MAN ES is expecting a high demand for a compact, cost efficient radial high-performance turbocharger for 2-stroke engines with up to 8300 kW[1].

Figure 3 shows the application ranges of the TCF series. The largest frame sizes are also offered as 2-stroke version.

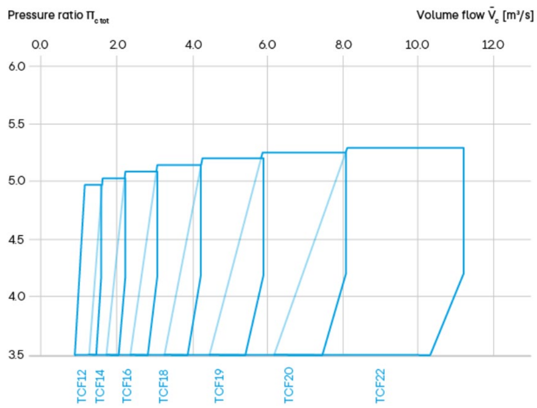

Figure 3: TCF application range

But the development target was not only on providing a turbocharger for 2-stroke engines. By performing the next development steps based on the TCT compressor technology, combined with

[1] Specific air consumption (l_e) 7.5 kg/kWh. Depends on fuel and engine type.

the newly developed part-load optimized radial turbine, the TCF characteristics and high specific turbocharger mass flow align with the expectations of medium-speed engine manufacturers of 1-stage medium-speed engines. Downsizing can be realized by a high specific turbocharger volume flow consequently resulting in smaller turbocharger components, higher acceleration, and a faster dynamic response.

Given that medium-load and part-load performance is a key focus in this project, the TCF turbocharger will serve as an additional and compact complement to the ECOCHARGE units for medium bore 4-stroke engines (see Figure 4). The system's 2-stage characteristic ensures good performance at relatively low-pressure ratios for each stage, while overall pressure ratios of up to 10.5 can be achieved.

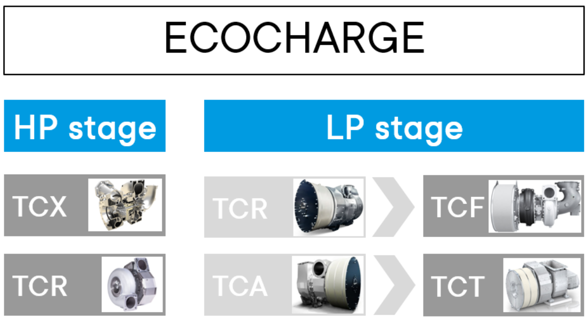

Figure 4: MAN ES ECOCHARGE two-stage product portfolio

All TCF frame sizes extend the fully flexible ECOCHARGE two-stage portfolio. Following the introduction of the TCT series as an optimized low-pressure stage for large medium-speed engines, the TCF series extends the range to include 30-bore medium-speed and smaller 4-stroke engines.

3 TURBOCHARGER VALIDATION

The TCF turbocharger has now progressed to the validation phase. As illustrated in the TCF project timeline in Figure 5, the numerical design phase has been successfully completed. Following a period of sourcing and procurement of both prototype and pre-series components, the testing phase started in mid-2023.

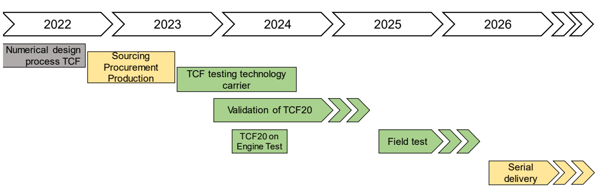

Figure 5: TCF development and validation timeline

Commencing with thermodynamic validation, a small frame size (TCF technology carrier) was initially employed for testing. Measurement data from the TCF technology carrier were utilized to generate compressor and turbine maps and to calibrate thermodynamic models. Early results from technology carrier also lead to modifications and optimization of components, which could be already implemented in first serial frame size TCF20.

Subsequently, TCF20 underwent testing at MAN's new turbocharger performance center (TPC) in Augsburg. The installation at the TPC is depicted in Figure 6. Initial tests again comprised thermodynamic maps, followed by further validation assessments such as high cycle fatigue (HCF), containment safety, rotor dynamics, SOLAS conformity, and others.

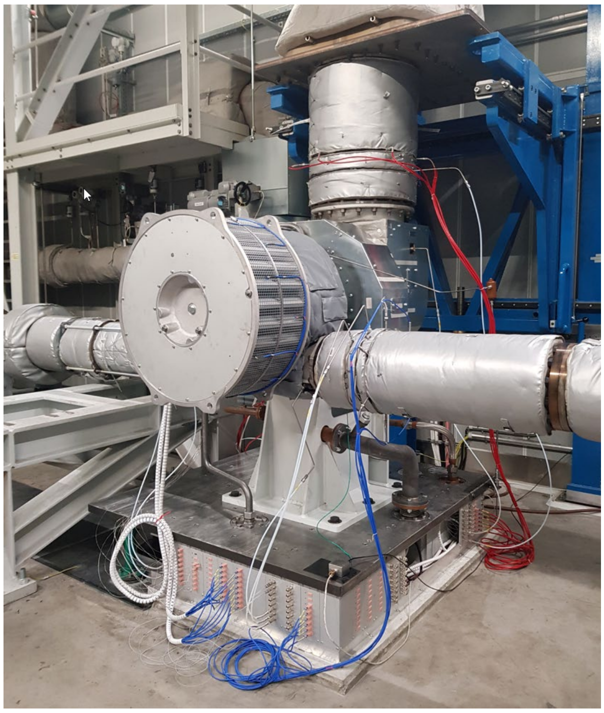

Figure 6: TCF20 on turbocharger test rig

Installation and operation on a 7L32/40 test engine was carried out simultaneously with tests of the turbocharger on TPC, which will be shown in chapter 4. Thermodynamic test results of the TCF technology carrier and TCF20 are presented in this chapter. Validation is planned to be continued with a field test so that TCF20 can be released for serial delivery in mid-2026.

3.1 Compressor validation

3.1.1 Compressor concept

The high-flow TCF turbocharger features an advanced high performance radial compressor stage, engineered for continuous operation at pressure ratios up to 5.0. The basic compressor geometry, already known from the TCT turbocharger, is designed to maximize specific volume flow without compromising performance. Key technical aspects include:

Compressor wheel design. The compressor wheel is optimized for high aerodynamic efficiency, featuring a sophisticated blade geometry that enhances flow characteristics and reduces losses.

Wide compressor map. The compressor stage is developed to provide a broad operating range, ensuring high efficiency across various engine speeds and loads. This is achieved through meticulous design and testing to balance surge and choke limits.

Efficiency characteristic. The compressor is designed to maintain high efficiency over a wide range of operating conditions, ensuring consistent performance and fuel economy across different engine loads and speeds. Figure 7 shows that the compressor can keep very high efficiencies over a wide range of the compressor map. This efficiency plateau contributes to the optimizability on part load for the TCF series.

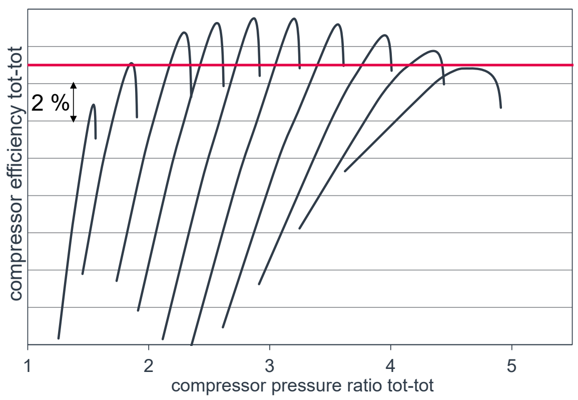

Figure 7: Compressor efficiency characteristic over pressure ratio

3.1.2 Compressor test results

The turbocharger was tested at the burner rig in the new Turbocharger Performance Center (TPC) in Augsburg, as shown in Figure 6. A comparison based on the test results is presented in Figure 8. The compressor map includes the TCR-41, the high-flow variant of the TCR series, and the TCF. It is evident that the TCF compressor geometry demonstrates approximately 20% higher specific flow. Additionally, the TCF exhibits a much wider compressor map, higher pressure capability, and significantly improved efficiency characteristics. These features result in a more robust and efficient compressor.

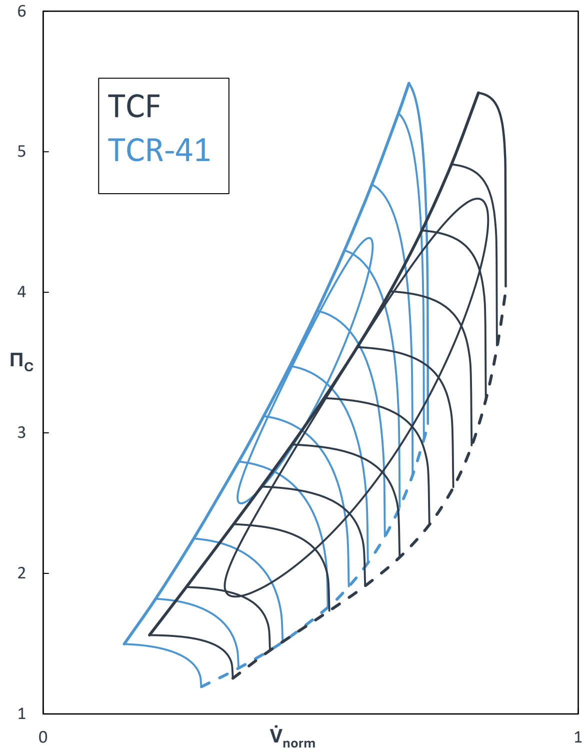

Figure 8: Comparison of TCF compressor map with current TCR-41 based on test results

3.2 Turbine Validation

The TCF turbine was developed to handle the high specific volume flow of the TCT compressor technology. As demonstrated by [3], the TCF turbine operates at the upper limit of what is achievable with a radial turbine in terms of specific volume flow. The trade-off between design constraints, stage characteristic numbers, structural mechanics, and casing size posed significant challenges. These challenges were successfully addressed and resolved during the development phase based on CFD driven geometry optimization.

3.2.1 Turbine specific flow rate

Specific reduced turbine flow rate (*VS*) is defined as

$$VS = \frac{\dot{V}_{\mathrm{t-in}}}{{D_{\mathrm{T}}}^{2} \cdot \sqrt{T_{\mathrm{t-in}}}} \qquad (1)$$

Where $\dot{V}_{\text{t-in}}$ is total volume flow rate at turbine inlet, $T_{\text{t-in}}$ is total turbine inlet temperature and D_{T} is the turbine characteristic diameter.

To get an impression of TCF turbine capabilities measurement results are compared to other radial turbines of turbochargers TCR20 and the older NR29/S, which was replaced by TCF20 on test engine 7L32/40. In Figure 9 minimum and maximum specific flow rate of the largest turbine meridian of each turbocharger type are plotted. The maximum specific volume flow is reached in combination with the largest nozzle ring, and the minimum specific flow with the smallest nozzle ring.

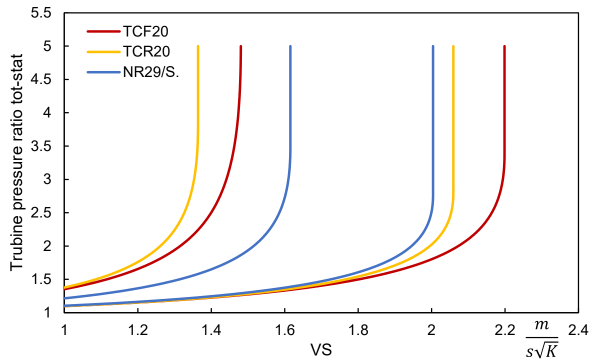

Figure 9: Comparison of specific turbine flow rate.

It is shown that the specific turbine flow rate at choking condition of TCF20 could be increased by 10% compared to NR29/S and by 7% compared to TCR20. It is also visible that the TCF20 turbine covers a wider range than its predecessors.

3.2.2 Matching turbine with compressor

Besides *VS*, which had to be maximized, another important stage characteristic number of the turbine is the blade speed ratio (*BSR*). It is defined as follows:

$$BSR = \frac{u_T}{\sqrt{2\, c_p T_{t-in}\left(1-\left(\frac{1}{\Pi_T}\right)^{(\gamma-1)/\gamma}\right)}} \qquad (2)$$

With turbine circumferential speed u_T, isobaric heat capacity c_p, total turbine inlet temperature $T_{t\text{-}in}$, total-total turbine pressure ratio Π_T and heat capacity ratio γ.

The turbine has to be matched to the compressor to have its operating line close to the turbines efficiency peak. This design target has to be reached in iterative manner. A commonly known rule is that turbine efficiency of radial turbines peaks at *BSR* around 0.7 [4], which serves as an initial value. The real *BSR* has to be calculated with CFD or measured. This optimization task has been addressed during development phase by calibration of thermodynamic models to CFD results.

Having a closer look to the turbines efficiency characteristics shows some important details. In Figure 10 an example of efficiency characteristics of two different turbine configurations are plotted versus turbine pressure ratio and *BSR*. Turbine rotor of both configurations is same but combined with two different nozzle rings, one with small ratio of stator to rotor throat area (A_S/A_R) and one with large A_S/A_R.

Also a typical compressor operating line is shown. The Effect of increasing the diameter ratio of turbine and compressor (D_T/D_C) is shown by the dashed line. Constrains for D_T/D_C are mechanical limits of the turbine wheel, cost and transient behaviour.

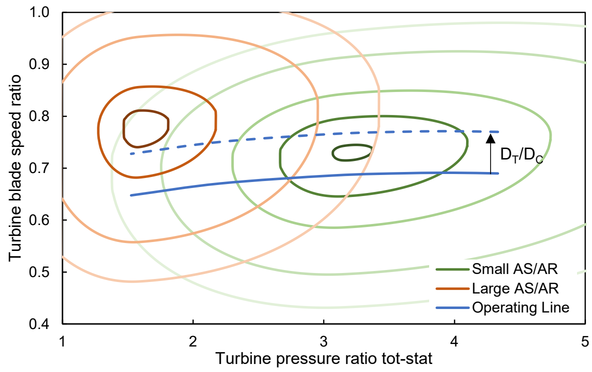

Figure 10: Schematic Turbine efficiency over turbine pressure ratio and blade speed ratio.

Small A_S/A_R leads to efficiency peak at high pressure ration and small *BSR* while large A_S/A_R has its peak at lower pressure ratio and slightly larger *BSR*. It is visible that peak efficiencies of both configurations are at *BSR* close to but larger than 0.7.

High part load efficiency and a part load optimized efficiency characteristic are two important development targets of TCF. While TCFs compressor map provides a high constant compressor efficiency along the engine operating line (see Figure 7), the turbine has to be applied to give the turbocharger a part load optimized efficiency characteristic. Therefore the compressor operating line has been placed close to part load efficiency peaks respecting above mentioned constraints regarding D_T/D_C.

This basic design task had to be addressed at a very early development stage. Therefore only CFD data of the turbine was available. This had to be combined with heat flux and friction models calibrated to measurements of similar machines. Finally the simulation results could be confirmed first with a technology carrier test and then within frame size TCF20.

TCF measurement results of turbocharger burner rig tests of three turbines with different A_S/A_R are shown in Figure 11.

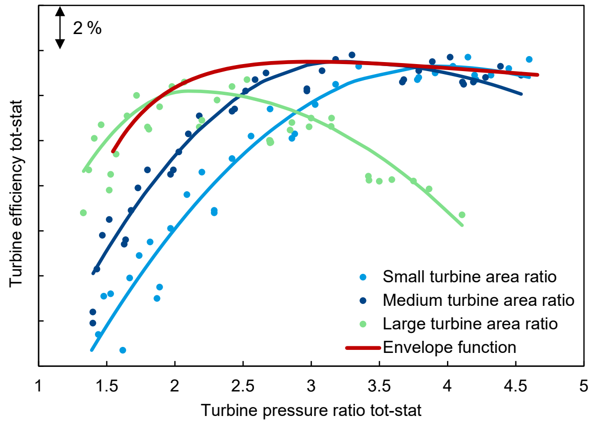

Figure 11: Turbine efficiency characteristics of three different TCF turbine configurations.

TCF turbine is configurable with a wide range of nozzle rings which means a wide range of stator-rotor area ratios (A_S/A_R), which defines the turbines load characteristic. Figure 11 explores how different turbine configurations shape the efficiency characteristics. A TCF turbine with small A_S/A_R has its efficiency peak at a pressure ratio of ~4 while a turbine with large A_S/A_R has its peak efficiency around pressure ratio 2.

3.2.3 Turbine efficiency benchmark

By connecting the peaks of each turbine efficiency curve an envelope function is created (see red line in Figure 11). This represents the peak efficiencies of all TCF turbine configurations. The flat course shows that high turbine peak efficiency is maintained for many different A_S/A_R configurations. Only peaks at turbine pressure ratios below 2, means of very large A_S/A_R ratios are a bit lower.

The same method was applied to create envelope functions for other radial turbines of turbochargers TCR20, NR29/S and TCX21 with very similar size as TCF20. These are plotted in Figure 12 to benchmark TCF20.

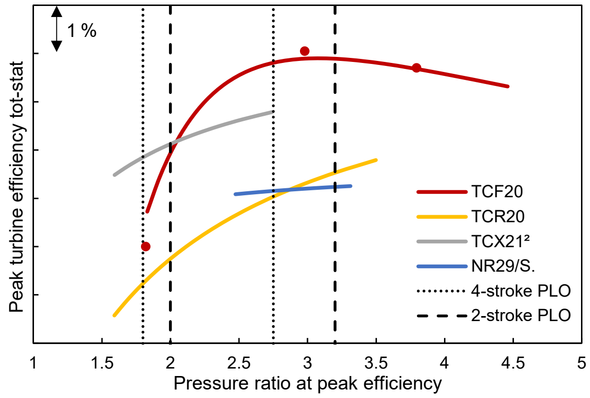

Figure 12: Comparison of TCF turbine with different other turbines of same size.[2]

TCF turbine peak efficiency curve covers a pressure ratio range from 1.8 up to 4.4, wider than the turbines of the other turbochargers. Means it has a larger variety of possible turbine A_S/A_R configurations. Also peak efficiency of TCF turbine of all possible A_S/A_R configurations is higher compared to almost all turbine configurations of TCR20, NR29/S and TCX21.

For the respective application on 32/40 engine NR29/S is the reference. Compared to NR29/S turbine efficiency of TCF20 is 2.5% points higher. Compared to TCR20 and its focus on high turbine pressure ratios turbine efficiency could be increased by more than 2%. And also compared to TCX21, which is a high-pressure turbocharger of a 2-stage turbocharging system with focus on very low pressure ratios [5], TCF20 turbine shows similar turbine efficiency.

In Figure 12 representative part load operation (PLO - 50% - 85% engine load) application ranges of 4-stroke and 2-stroke engines are marked. This means that efficiency of TCF20 turbine can be configured to have its peak efficiency at 50% engine load of a 4-stroke engine and below 50% of a 2-stroke engine.

The test program not only covered the largest meridians. Different turbine meridians, from the smallest to the largest, have been tested and show only minor effects on turbine efficiencies. This means that high efficiency is maintained across the complete capacity range of each TC frame size.

The wide A_S/A_R range is covered by multiple nozzle rings with different vane geometries and vane angles. Achieving and ensuring sufficient HCF resistance for all rotor-stator combinations in this

[2] TCX21 efficiency is total-total definition.

area is challenging. New methods were applied to develop a robust design early in the process [6]. This way the desired A_S/A_R-range could be finally confirmed by HCF tests.

4 TCF20: 32/40CD EFFICIENCY PACKAGE

The TCF turbocharger series is initially being introduced for MAN's 32/40CD engine family.

This engine has been produced in large quantities by MAN ES licensees for many years, with nearly 4,000 units in operation worldwide. Additionally, around 100 licensed engines are still being built annually. Known for their reliability and performance, these engines, combined with exceptional service support, offer a highly attractive package for customers. This is why MAN Energy Solutions has decided to prepare this engine for future requirements and ensure its competitiveness by upgrading the 32/40CD.

The introduction of the new TCF turbocharger to the 32/40CD engine series offers significant potential for improvement. However, the goal is not merely a "simple" turbocharger retrofit, but a comprehensive engine optimization. Therefor several objectives have been set for this project:

- improve performance
- reduce specific costs
  - reduce complexity
  - reduce number of engine variants
- design for modular solutions

In the center of these improvements is the turbocharger series TCF. Compared to the current 32/40CD turbochargers (NR29/S, NR34/S, and the newer TCR series), the design improvements of the TCF are the enablers in achieving these targets.

4.1 Performance

A significant advantage of the new 32/40CD configuration is its enhanced efficiency, primarily achieved by boosting the turbocharger's performance. This improvement is crucial for enhancing the engine's fuel economy and reducing CO_2 emissions, all without requiring major modifications to the engine.

Through discussions with customers and analysis of 32/40CD operation data by using MAN's valuable real-time digital data monitoring platform CEON, the specific requirements for this engine type were identified.

Often used as (auxiliar) genset on vessels with bigger main engines, many customers see the necessity to optimize the engine for part-load operation. Figure 13 shows a typical load profile from this analysis. Because of the high load share in the area from 30%– 60% load depending on the application type, the optimization focused on these loads.

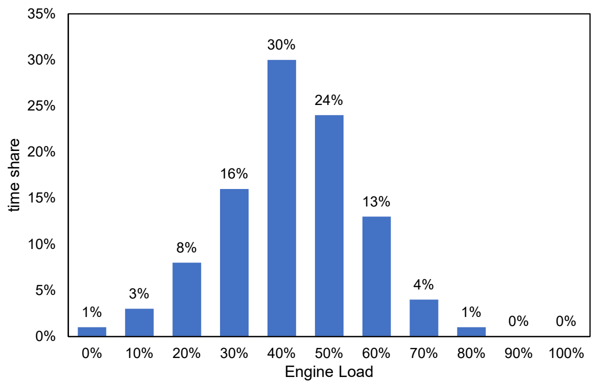

Figure 13: Typical customer load profile

4.2 Specific costs

Another big step to achieve several of the project targets for the 32/40CD engine is the improved specific flow capacity of the TCF turbocharger series. Because of the high-volume flow capability, 6-9 cylinder variants of this engine can be covered by only one turbocharger frame size. The 32/40CD engine is equipped with TCF20 for all cylinder numbers, where previously two frame sizes (NR29/S and NR34/S) were needed. Using only one instead of two turbocharger frame sizes is reduces variants and specific costs significantly. For the V-engine configuration from 12–18 cylinders each of the two lines is equipped with the small TCF20 turbocharger.

Furthermore, by optimizing the turbocharger under partial load, it was possible to eliminate the need for variable injection timing (VIT). In 32/40CD engines with older turbochargers, VIT was necessary to reduce soot emissions at partial load by adjusting the injection to an earlier timing, thereby improving the combustion process. By optimizing the combustion process, the engine was able to maintain low soot levels, even though the NR turbocharger provided charge air for rich operation only at lower loads. For high loads, later injection timing was required to stay within the mechanical limits of the engine and turbocharger, as well as to meet NOx emission limits. Although this system has evolved into a highly reliable solution, eliminating the VIT reduces engine complexity, thereby increasing cost efficiency and minimizing service effort.

In addition to those developments, the project team decided to reduce the number of engine variants in number by almost 50%. In combination with the reduced complexity of the engine and the increased engine performance, in terms of both cost and mechanical performance the 32/40CD is going to be a competitive product for the future.

4.3 Modularity

The TCF turbocharger was designed not only as a high-performance turbocharger with a high specific volume flow but also with the early intention of performing an efficiency upgrade for the 32/40CD engine.

As a result, the TCF20 frame size was specifically adapted to replace the original NR29 and NR34 turbochargers without requiring modifications to the engine design or components. This modularity and plug-and-play characteristic are essential not only to upgrade the efficiency of newly built engines but also for various retrofit concepts.

Figure 14: 7L32/40CD test engine

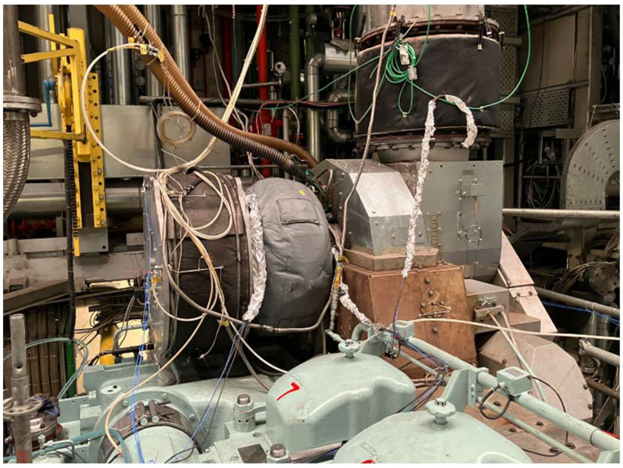

Figure 15: TCF20 on test engine

4.4 Retrofit set-up for 32/40CD engines

Given the substantial population of existing units, it is essential that not only newly built engines benefit from these upgrades. A primary objective is to enhance the retrofit capability for the approximately 4,000 engines currently in operation. This approach will ensure that the benefits of the latest advancements are accessible to the entire fleet, thereby maximizing performance and efficiency across the board.

For retrofit solutions, it is crucial to consider the specific situation on-site. On one hand, a VIT system may already be installed on potential retrofit engines, and it would not make sense to remove these effective systems. On the other hand, the VIT provides the engine with an additional degree of freedom, allowing the exhaust gas waste gate (WG) to be omitted. Therefore for newly-built engines and retrofit purposes, different turbocharger specifications must be provided.

5 TCF20 ON ENGINE TEST

At the beginning of 2024 MAN Energy Solutions was testing the 7L32/40CD engine with the new TCF20 for the first time.

The objective of this engine test was twofold: first, to validate the TCF performance under real operational conditions, and second, to validate the 32/40CD upgrade, ensuring a future perspective for this engine type. This includes considerations for the Efficiency package and providing evidence for retrofit solutions.

Figure 14 and Figure 15 show the 7L32/40CD test engine equipped with the TCF20 turbocharger at the MAN Energy Solutions engine test facility at the company’s Augsburg headquarters. Numerous cables and hoses are visible around the turbocharger, because for this prototype, additional sensors for temperature and pressure have been installed to ensure proper validation of performance and mechanical load.

5.1 Performance results

Figure 16 presents test results comparing a 32/40CD engine equipped with the current series NR turbocharger to the same engine fitted with the new TCF prototype. The comparison highlights the charging efficiency and specific fuel oil consumption (SFOC) of the engine, as shown by the black and blue lines in Figure 16.

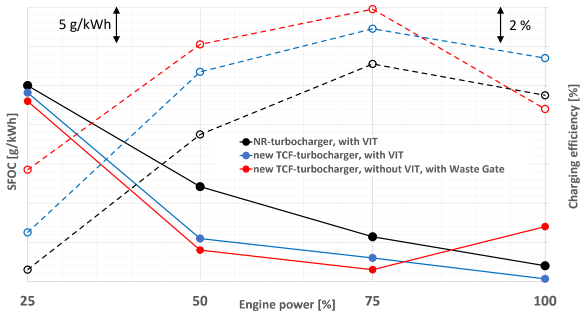

Figure 16: Comparison between engine with NR and TCF

The blue line represents one retrofit variant without a waste gate and with VIT. This configuration is nearly a 1:1 replacement of the NR turbocharger with the TCF, resulting in an efficiency gain of more than 2% across almost the entire engine load range. The only difference is the higher charge air potential of the TCF series, which leads to additional fuel consumption benefits beyond the turbocharger efficiency. Figure 16 and Figure 17 present the test results for this engine variant. Although the retrofit configuration does not fully exploit the part-load optimization potential of the TCF series, the positive effect remains remarkable.

However, the Efficiency Package results in even higher part load efficiencies. The combination of a part-load optimized turbine and increased charge air pressure reduces SFOC by more than 4g/kWh at 75% engine load The red lines illustrate this performance variant without the VIT. At 50% engine power, the fuel savings even exceed 8g/kWh, whereas at 100% engine power, no improvement is observed. This is due to the strategic decision to focus on part-load performance and the application of the exhaust gas waste gate. The explanation is visible in the same diagram. While charging efficiency at part load increases by up to 5%, the bypass of exhaust gas negates this advantage at full load, despite the turbocharger's higher efficiency potential at high loads.

A simple calculation in Table 1 demonstrates the fuel consumption together with the reduction in CO_2 emissions resulting from a specific fuel consumption reduction of 5g/kWh over one day and one year. At 50% engine load, this is the reduction expected; at lower loads the reduction is even greater. According to the table, the annual savings in fuel oil consumption at part load can exceed 192metric tons/year. Besides the cost savings, this measure results in a remarkable reduction of 603metric tons/year of CO_2 emissions. Considering that large diesel engines operate for decades, the long-term impact is substantial.

Table 1: Reduction of fuel consumption and CO_2-emissions reduction over one day and one year for a 12V32/40 CD engine as example

Engine	*12V32/40CD*	
Engine Power 100% load in kW	6000	kW
Fuel consumption per day (21 operating hours)	13	tonnes
Fuel consumption per Year (6000 operating hours not uncommon)	3600	tonnes
Reduction in spec. fuel consumption	8	g/kWh
Fuel consumption savings per day*	0.5	tonnes
Fuel consumption savings per year*	192	tonnes
CO2 emissions savings per day*	1.6	tonnes
CO2 emissions savings per year*	603	tonnes

*-Assumption: engine operation at 50% engine load

The enhanced efficiency of the TCF turbocharger improves exhaust gas temperature behavior at part-load conditions (see Figure 17). From 75% engine load, the exhaust gas temperature before the turbine is lower, providing a greater margin to the temperature limit. This additional margin enhances resilience against various ambient conditions such as temperature, altitude, fuel quality, fouling, and wear. The new tuning also results in a more stable temperature trajectory after the turbine, with the temperature remaining almost constant over a wide load range. This characteristic is highly beneficial for an SCR catalyst downstream of the engine, reducing the effort required by the control unit to maintain the temperature within the optimal operating window for the SCR.

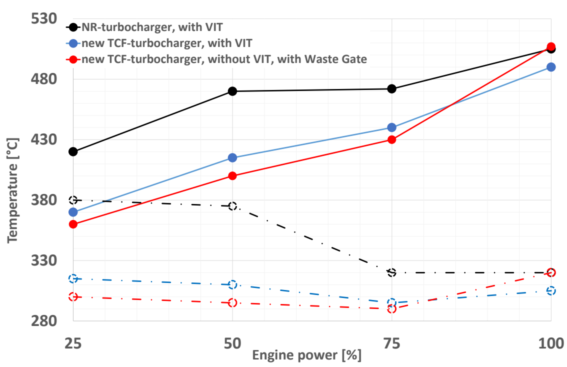

Figure 17: Comparison between engine with NR and TCF turbocharger. Exhaust gas temperature and charging efficiency.

During the test campaign, the turbocharger demonstrated the expected wide compressor map and exhibited strong stability against surging. Despite various methods, surging could not be induced, highlighting another potential for cost reduction with the TCF turbocharger. Due to its very stable operation, application engineers can address uncertainties in engine data, such as calculation inaccuracies or production tolerances, without resorting to variant parts for compensation. It is common practice to specify additional diffusers to compensate for variations in compressor volume flow and to change the diffusers during turbocharger matching. The engine test results suggest that the need for variation parts can be significantly reduced in many cases.

Despite the bigger rotor in the TCF20 compared to the NR29, a similar or better transient behavior could be realized by combining the advantages of the new charging system with higher efficiency especially at part load and a higher charge air pressure.

6 CONCLUSION

The new TCF series, aimed at enhancing current engines and retrofitting existing systems, was successfully tested on the upcoming release of the 32/40CD family.

Due to the part-load characteristic of the turbocharger, it is possible to increase the charge air pressure at all operation points, creating excess air and resulting in low soot emissions. Without the TCF optimization, an increased charge air pressure would cause a drop of efficiency at part load, and the soot reduction could not be achieved.

In combination with the charge air control using the waste gate at 100% load for new built engines, the maximum turbocharger speed and the maximum permissible cylinder pressure are maintained. This not only improves performance and efficiency, but also reduces costs as the VIT is no longer required.

Based on customer load profiles, the test engine had to prove that the part load optimization was successful. The new turbocharger enables more efficient operation in the part-load range between 25% and 85% engine load in all configurations. This range corresponds to the most frequently driven loads (compare Figure 13) and therefore enables a significant increase in efficiency in day-to-day operation. This results in lower fuel consumption and, consequently, lower CO_2 emissions (see also Figure 16 red lines).

These new 32/40CD applications with TCF turbochargers are not only more efficient but also comply with the new NOx Technical Code 2027 of the International Maritime Organization (IMO), making them a future-proof solution. Overall, the Retrofit and Efficiency Package for 32/40CD engine with the new TCF turbochargers represents a sensible investment that offers both economic and ecological benefits. It enables the sustainable utilization of existing engines and at the same time helps to reduce emissions, which is in line with global efforts to combat climate change.

However, not only MAN 32/40 engines will benefit from the TCF turbocharger series. The TCF will contribute to emission reduction for new build engines and improve the EEDI rating. Additionally, retrofitting existing engines will enhance evaluations for the EEXI and CII indices.

7 ABBREVIATIONS

A_R	Rotor throat area
A_S	Stator throat area
BSR	Turbine blade speed ratio
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
D_C	Compressor diameter
D_T	Turbine diameter
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGR	Exhaust Gas Recirculation
GHG	Greenhouse Gas
HCF	high cycle fatigue
HP stage	high-pressure stage
IMO	International Maritime Organization
LP stage	low-pressure stage
MAN ES	MAN Energy Solutions
PLO	Part load operation 50% - 85%
SCR	Selective Catalytic Reduction
SFOC	specific fuel oil consumption
SOLAS	International Convention for the Safety of Life at Sea
TCF	High flow radial turbocharger series
TCP	High pressure ratio turbocharger

TCX	High Pressure stage turbocharger
TPC	Turbocharger performance center
Tt-in	total turbine inlet temperature
VIT	variable injection timing
VS	Specific reduced turbine flow rate
$\dot{V}$t-in	total volume flow rate at turbine inlet
WG	Waste gate

8 REFERENCES AND BIBLIOGRAPHY

[1] International Maritime Organization, “2023 IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS,” London, 2023.

[2] S. Mayr, M. Stork, S. Eisenbach, S. Spengler and P. Toshev, “Turbocharger Innovations for Compliance with Tier III Emission Limits,” in *CIMAC Congress*, Vancouver, 2019.

[3] M. Stork, F. Grießhaber, L. Aurahs, S. Münch, S. Weihard and M. Michael, “Development of a high flow (TCF) and ahigh pressure (TCP) radialturbocharger series,” in *CIMAC Congress*, Busan, 2023.

[4] N. Watson and M. Janota, Turbocharging the Internal Combustion Engine, The Macmillan Press Ltd., 1982.

[5] D. Albrecht, H. Benetschik and H. Schmuttermair, “Die TCX-Baureihe - Eine neue Generation zweistufiger Aufladesysteme,” in *18. Aufladetechnische Konferenz*, Dresden, 2013.

[6] S. Spengler, C. Leitenmeier, H. Benetschik, T. Willeke and L. Aurahs, “High Cycle Fatigue – Advanced development and design methods for increased robustness,” in *CIMAC Congress*, Busan, 2023.

9 CONTACT

Martin Kern
E-mail: Martin.Kern@man-es.com

Matthias Müller
E-mail: Matthias.Mueller.c@man-es.com

Dr. Maxim Epp
E-mail: maxim.epp@man-es.com

MAN Energy Solutions SE
Stadtbachstr. 1, 86153 Augsburg, Germany

URL: https://www.man-es.com/

PBST - a brand of MAN Energy Solutions SE
Stadtbachstr. 1, 86153 Augsburg, Germany

URL: https://www.pbst.eu/