EPA T4 / IMO III emissions compliance without urea after-treatment

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Abstract

The adverse impact of air pollutants to human health, particularly NO_X, particulate matter and SO_X, has triggered emissions regulations in several industry sectors, including the marine sector. Air pollutants in sea going ship's exhaust gasses are governed by increasingly more stringent emission standards defined in the International Maritime Organization's Maritime Pollution Convention Annex VI. U.S. flagged ships operating in U.S. waters or in the designated North American and U.S. Caribbean Sea environmental control areas must comply with the emissions limitations defined in the U.S. Code of Federal Regulations, title 40 part 1042, governed by the Environmental Protection Agency.

A common methodology used to meet the IMO III or EPA T4 NO_X emission standards is reducing NO_X in the exhaust gas through deployment of a Selective Catalytic Reduction (SCR) exhaust gas after-treatment system. An alternative methodology to meet the IMO III or EPA T4 standards is to minimize formation of NO_X in-cylinder through deploying Exhaust Gas Recirculation (EGR) technology. In 2015, after 6 years of development, GE Transportation, a Wabtec company (Wabtec), has been first to launch a medium-speed marine diesel engine series that is certified to meet the IMO III and EPA T4 standards through an advanced EGR system, while maintaining world class fuel efficiency.

This paper will describe Wabtec's advanced EGR technology and detail results from independent evaluation studies comparing propulsion configurations based on engines with EGR technology versus those with SCR after-treatment technology on the following aspects: (i) system weight and size; (ii) installation cost; and (iii) operating cost.

1. Introduction

About 91 percent of the world's population now lives in places where air pollution levels exceed air quality guidelines set by the World Health Organization [1]. Air pollution is now the 5th highest cause of death among all health risks, ranking just below smoking. Each year, more people die from air pollution related disease than from road traffic injuries or malaria [2]. The harmful impact of air pollutants to human health, particularly NO_X, particulate matter, and SO_X, have triggered emissions regulations in several industry sectors, including the marine sector. Air pollutants in sea going ship's exhaust gas are governed by increasingly more stringent standards defined in the International Maritime Organization's (IMO) Maritime Pollution Convention (MARPOL) Annex VI [3]. U.S. flagged vessels operating in U.S. waters or in the designated North American and U.S. Caribbean Sea Environmental Control Area (ECA) must comply with the emissions limitations defined in the U.S. Code of Federal Regulations (CFR), Title 40 Part 1042 [4], governed by the Environmental Protection Agency (EPA).

To reduce the SO_X emitted from ships, the IMO has set the limit for sulfur content in fuel oil used by ships at 0.1% for ships operating in the designated Sulfur Emission Control Areas (SECA) of the North Sea, Baltic Sea, North America and U.S. Caribbean Sea after January 1, 2015. IMO has set the limit at 0.50% for ships operating outside designated SECAs after January 1, 2020. Ships may also meet the SO_X emission limit by using exhaust gas cleaning systems ("scrubbers"), which reduce the SO_X amount in the exhaust gas before it is released into the atmosphere [5].

IMO's MARPOL Annex VI, Chapter 3, Regulation 13.5.1.1 [6] defines the limits for NO_X emitted from ships. For ships constructed on or after January 1, 2011, the NO_X limit is set depending on engine's rated rpm between 7.7 to 14.4 g/kWh (Tier II). The NO_X limit is set between 2.0 and 3.4 g/kWh (Tier III) for ships constructed on or after January 1, 2016 and operating in the North American and U.S. Caribbean ECAs, and for ships constructed on or after January 1, 2021 and operating in the Baltic Sea ECA or the North Sea ECA.

Refer to table 1 for a comparison of the emission standards for compression-ignition marine engines governed by the IMO and EPA.

Standard	Engine category	CO g/kWh	HC g/kWh	NO_x g/kWh	PM g/kWh
IMO II	$P > 130$ kW $n<130$ $130 \le n < 2000$ $n \ge 2000$	n/a	n/a	7.7 – 14.4 = 14.4 $= 44\ n^{(-0.23)}$ = 7.7	n/a
IMO III	$P > 130$ kW $n<130$ $130 \le n < 2000$ $n \ge 2000$	n/a	n/a	2 - 3.4 = 3.4 $= 9\ n^{(-0.2)}$ = 2	n/a
EPA T4	$600 \le P < 2000$ $2000 \le P < 3700$ $P \ge 3700$ Class 3: SV ≥ 30 l	5.0	0.19 0.19 0.19 2.0	1.8 1.8 1.8 Per IMO III	0.04 0.04 0.06 n/a

Table 1. Comparison of the emissions standards for compression-ignition marine engines governed by IMO and EPA

A common methodology used to meet the IMO III or EPA T4 NO_X standards is reducing NO_X in the exhaust gas through deploying a Selective Catalytic Reduction (SCR) exhaust gas after-treatment system. A reductant – usually a urea solution – is injected in the exhaust and funneled through a mixing chamber to a reactor containing a catalyst that enables a series of chemical reactions: urea is converted to ammonia and carbon dioxide, and the ammonia subsequently reacts with nitrogen oxides to yield nitrogen and water. The SCR after-treatment technology requires space and weight provisions for urea tanks, dosing pumps, stainless-steel piping, mixing chambers and the SCR reactors. Other disadvantages of urea after-treatment systems include the complications associated with handling urea on board the ship (urine-like odor), controlling ammonia slip, the incremental operational cost for consuming urea, and additional maintenance scope.

An alternative methodology to meet the IMO III or EPA T4 standards is to limit the formation of NO_X in-cylinder through deploying Exhaust Gas Recirculation (EGR) technology. GE Transportation, a Wabtec company (Wabtec), has been first to launch a medium-speed marine diesel engine series which is certified to meet the IMO III and EPA T4 NO_X standards through advanced EGR technology.

This paper will describe Wabtec's EGR technology and detail results from independent evaluation studies comparing propulsion configuration based on engines with EGR technology versus those with SCR after-treatment technology on the following aspects: (i) system weight and size; (ii) installation cost; and (iii) operating cost.

2. EGR technology – how it works

Wabtec's advanced EGR solution, minimizes the formation of NO_X during combustion as opposed to reducing NO_X in the exhaust through a series of chemical reactions in an after-treatment system. This is accomplished through a combination of several technologies:

- EGR. Depending on the engine load, a certain portion of the exhaust gas is cooled and mixed with fresh compressed and cooled combustion air, and subsequently routed into the cylinders. This enables the reduction of the combustion temperature in the cylinder that minimizes NO_X formation.

While a lower combustion temperature results in less NO_X formation, it could also result in a lower fuel efficiency if no other technologies are deployed. With GET's advanced EGR solution, we maintain a fuel efficiency equal or better than that of our comparable IMO II emissions engine series through:

- Increased peak-cylinder-pressure, enabled by structural improvements and a two-stage turbocharging arrangement with intercooling and aftercooling
- Finer fuel atomization enabled by a 2200 bar capable high-pressure common rail fuel system
- Advanced combustion controls
- Optimized Miller cycle

Refer to figure 1 for details of the air handling and EGR system layout for the V250 series.

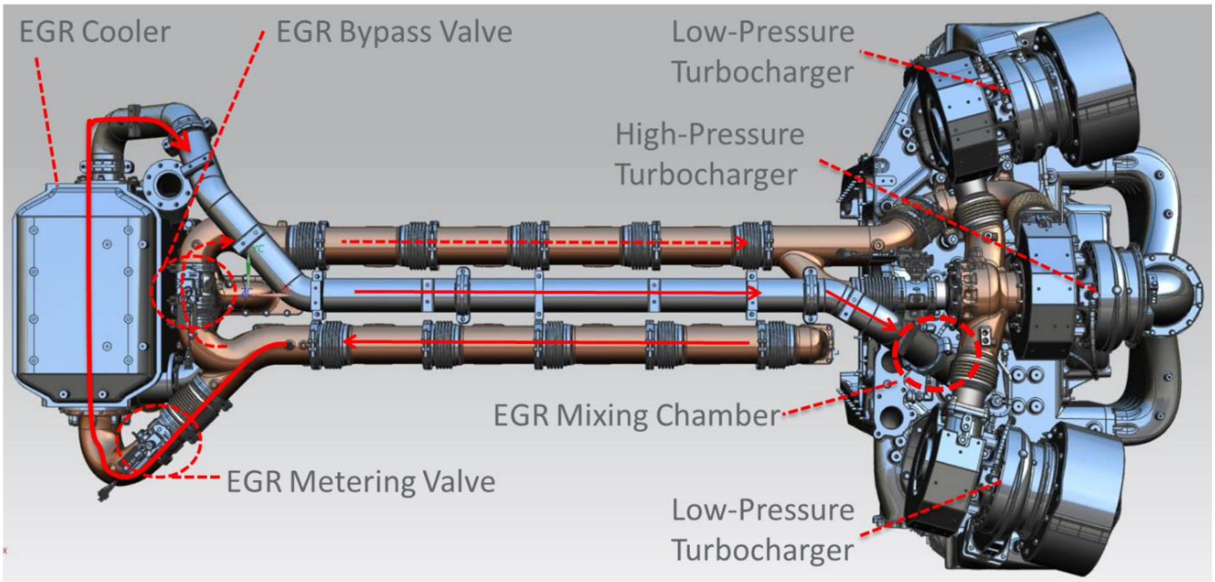


Figure 1. Air handling and EGR system layout for 12V250MDC engine

3. EGR system weight and size benefits

Engines with this advanced EGR solution offer significant system weight and size benefits compared to engines with a SCR after-treatment system that includes additional equipment scope such as a urea tank, a dosing pump, an injector system, a mixing tube, a SCR catalyst and housing, and a SCR control system and cabinet. Figure 2 illustrates the additional equipment scope for a system based on SCR after-treatment technology versus EGR technology.

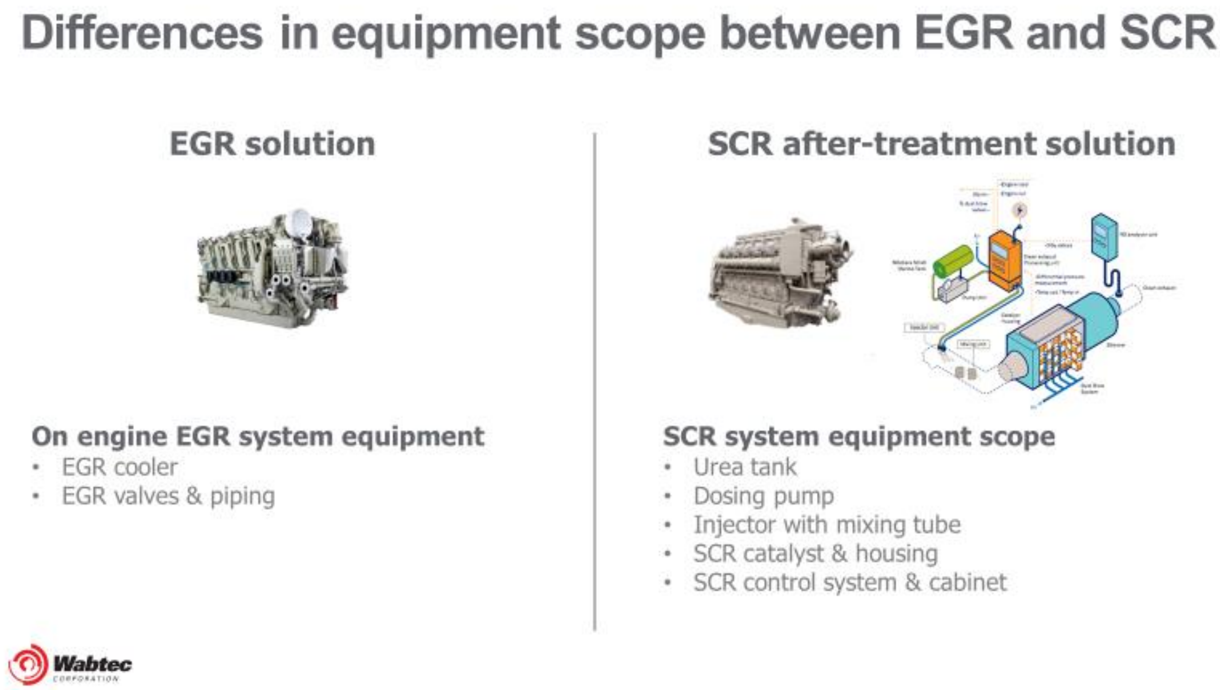


Figure 2. Difference in equipment scope for EGR and SCR technology

Jensen Maritime Consultants evaluated the system weight and size for three different EPA T4 compliant propulsion engine configurations: (i) two medium-speed engines with Wabtec's EGR solution (each 2,500 bkW @ 1,000 rpm); (ii) two medium-speed engines with SCR after-treatment technology (each 2,600 bkW @ 900 rpm); and (iii) two high-speed engines with SCR after-treatment technology (each 2,460 bkW @ 1,800 rpm). The study [7] concluded that for a 497 gross ton line haul tug with enough urea on board for 90 days the configuration based on medium-speed engines with EGR technology:

- had a 50% lower system weight and required 40% less space relative to the configuration based on medium-speed engines with SCR
- had a 30% lower system weight and required 20% less space relative to the configuration based on high-speed engines with SCR

Space & weight savings of EGR vs. SCR

EGR solution requires up to 50% less weight and up to 40% less space

Solution based on 2 x Wabtec Medium Speed with EGR

@ 1000 rpm 2500 bkW

	Weight (kg)	Volume (m^3)
Engines (2)	49,532	68.3
Mixing Tubes (2)	N/A	N/A
SCR (2)	N/A	N/A
Dosing Cabinets (2)	N/A	N/A
Air Compressors (2)	N/A	N/A
Transfer Pump (optional)	N/A	N/A
Control units (2)	N/A	N/A
Urea Storage (1)	N/A	N/A
Total	**49,532**	**68.3**

Solution based on 2 x Medium Speed with SCR

@ 900 rpm 2600 bkW

	Weight (kg)	Volume (m^3)
Engines (2)	43,200	54.18
Mixing Tubes (2)	260	1.8
SCR (2)	3,800	8.42
Dosing Cabinets (2)	190	1
Air Compressors (2)	80	0.5
Transfer Pump (optional)	80	0.5
Control units (2)	150	2
Urea Storage (1)	50,000	50
Total	**97,760**	**118.4**

Solution based on 2 x High Speed with SCR

@ 1800 rpm 2460 bkW

	Weight (kg)	Volume (m^3)
Engines (2)	16,056	25.72
Mixing Tubes (2)	Incl	Incl
SCR (2)	2,780	8.58
Dosing Cabinets (2)	190	0.52
Air Compressors (2)	80	0.5
Transfer Pump (optional)	80	0.5
Control units (2)	N/A	N/A
Urea Storage (1)	50,000	50
Total	**69,186**	**85.82**

Figure 3. System weight and space comparison

4. EGR system installation cost benefits

Engines with EGR technology offer significant installation cost benefits compared to engines with a SCR after-treatment system. Jensen Maritime Consultants evaluated the installation cost for three different EPA T4 compliant propulsion engine configurations: (i) two medium-speed engines with Wabtec's EGR solution (each 2,500 bkW @ 1,000 rpm); (ii) two medium-speed engines with SCR after-treatment technology (each 2,600 bkW @ 900 rpm); and (iii) two high-speed engines with SCR after-treatment technology (each 2,460 bkW @ 1,800 rpm). The study assessed the installation cost comprised of major material, equipment, and labor, taking the following scope into account:

- SCR after-treatment system, including stainless steel tank and piping for urea
- engine jacket water and aftercooler heat rejection and associated impact on keel cooler
- ambient heat rejection from the engines and associated exhaust after-treatment equipment, including impact on engine room ventilation requirements
- engineering cost associated with replacing high-speed engines with medium-speed engines.

To provide a basis for the comparison, design elements from Jensen's 100 ft assist/escort tug and 128 ft ATB tug were used to estimate the engine room ventilation requirements and urea tank design. Refer to table 2 for the basic attributes of these tugs.

Attribute	Assist/Escort Tug	ATB Tug
LOA	100'-0"	128'-0'
Beam	40'-0"	42'-0"
Max Draft	19'-6"	18'-0"
Installed Power	6,800 hp	6,600 hp
Bollard Pull	90 short tons	

Table 2. Attributes of Tugs used for evaluation of installation cost

The study was based on the following assumptions and exclusions:

- Single, independent urea tank with 4,500 gallons capacity
- Engine foundations were excluded
- Keel coolers were assumed for estimating the impact on the high and low temperature heat rejection circuit components. The keel cooler guard estimates are based on Jensen's standard keel cooler guard detail.
- The SCRs were assumed to be installed in the engine room for the purpose of estimating ventilation requirements
- Capital cost of the engines and other associated components have been excluded from this study
- Shipyard markup on procured equipment and margin on fabrication and installation work was assumed to be 15%
- Shipyard labor rates used in this study are as follows:
    - US Pacific Northwest: $90/hr
    - US Gulf Coast: $55/hr
    - Europe: $35/hr
    - Asia: $15/hr

Additional assumptions are listed in Appendix A.

Equipment and material costs were solicited for the keel coolers, engine room ventilation fans, steel plate, and steel pipe. Steel prices for Asia and Europe were calculated by adjusting U.S. prices by the relative difference in global pricing in U.S. dollars per metric ton for hot-rolled band. The values used in this study were calculated from October 2019 benchmark data, which includes the effects of a 25% U.S. tariff on imported steel.

4.1 Urea system

The requirement for urea is the biggest factor when evaluating the installation cost differences between engines with EGR and SCR technology. The study took the following equipment and components into account for the urea system: (i) urea tank, foundation, vent, and fill piping; (ii) urea tank insulation and heating allowance; (iii) foundations for SCR housing; (iv) two urea transfer system pumps, piping, fittings, and valves; (v) compressed air piping, valves and fitting for the dosing units; (vi) miscellaneous electrical requirements for power, control, and monitoring of dosing equipment and tank level indication.

The common design practice in a tugboat application is to construct one or more independent urea tanks out of stainless steel. Additionally, the urea transfer system is commonly constructed out of stainless steel. The urea tank volume is typically sized based on the duty cycle of the ship and availability of urea. As a rule of thumb, the urea tank is often sized at six to ten percent of the ship's fuel capacity. For the purpose of this study a single independent tank with a 4,500 gallons capacity was used as a reasonable size for a harbor or ATB tug application. Temperature requirements for urea handling and storage generally demand provisions for tank heating and insulation. For the purpose of this study, the tank was assumed to be fitted with electric strip heaters.

Table 3 shows the results of the estimated cost to design, fabricate, and install the urea tank and system.

Region	**Estimated cost**
Pacific Northwest	$374,065
Gulf Coast	$315,937
Europe	$256,529
Asia	$204,523

Table 3. Estimated cost to design, fabricate, and install the urea tank and system

4.2 Engine jacket water and after cooler heat rejection

Engine jacket water and aftercooler cooling systems are required for all three propulsion engine configurations considered in the study. The impact on installation cost was evaluated for each configuration based on comparing the estimated heat rejection values and sizing the appropriate keel coolers. The cost of fabricating and installing keel cooler guards were also factored into the evaluation. The flowrates for the cooling systems are similar for the three propulsion engine configurations, so the cooling system pipe sizes were assumed to be equivalent. Keel coolers were sized assuming a zero knot current, which is typical for tugboat applications.

Table 4 provides a summary of the estimated heat rejection values for each configuration. The medium-speed engine with EGR has the highest heat rejection values and thus required the greatest cooling capacity.

	Medium-speed EGR	Medium-speed SCR	High-speed SCR
Jacket water	1,304 kW	400 kW	1,000 kW
After cooler	1,215 kW	1,300 kW	400 kW

Table 4. Heat rejection values

Table 5 shows the results of the estimated cost to fabricate and install the keel coolers and guards.

	Medium-speed EGR	Medium-speed SCR	High-speed SCR
Pacific NW	$361,967	$343,133	$317,237
Gulf Coast	$347,813	$330,496	$305,611
Europe	$266,736	$258,106	$239,021
Asia	$260,508	$252,545	$233,896

Table 5. Estimated cost to fabricate and install keel coolers and guards

4.3 Engine room ventilation

Engine room ventilation requirements were calculated for each configuration using estimated ambient heat loads. In order to provide a more comprehensive analysis, the engine's heat loads were factored into the ventilation calculations along with generators, auxiliary mechanical equipment, and electrical equipment. The calculations were used to estimate ventilation fan sizing. For the purpose of this study, the SCRs were assumed to be installed in the engine room and were also factored into the ventilation requirements. The ambient heat rejection values (Btu/hr) at 85% load per engine used for this study, the associated engine room ventilation requirements (cfm), and the estimated cost for the engine room ventilation fan cost are shown in table 6.

It is important to note that the America Bureau of Shipping's Guide for Exhaust Emission Abatement requires a minimum of six air changes per hour in areas where urea tanks are located. For the purpose of this study, the urea tank was assumed to be placed in the steering gear room. These spaces have ventilation systems sized to limit the temperature rise in the space and typically meet the minimum air change requirement. Consequently, the impact on installation costs associated with the urea tank ventilation was assumed to be negligible.

	Medium-speed EGR	Medium-speed SCR	High-speed SCR
Engine ambient heat rejection	273,564 Btu/hr	350,000 Btu/hr	170,000 Btu/hr
SCR ambient heat rejection	n/a	170,000 Btu/hr	170,000 Btu/hr
Total ambient heat rejection	273,564 Btu/hr	520,000 Btu/hr	340,000 Btu/hr
Ventilation	38,000 cfm	57,000 cfm	40,000 cfm
Fan cost	$11,684	$13,984	$12,777

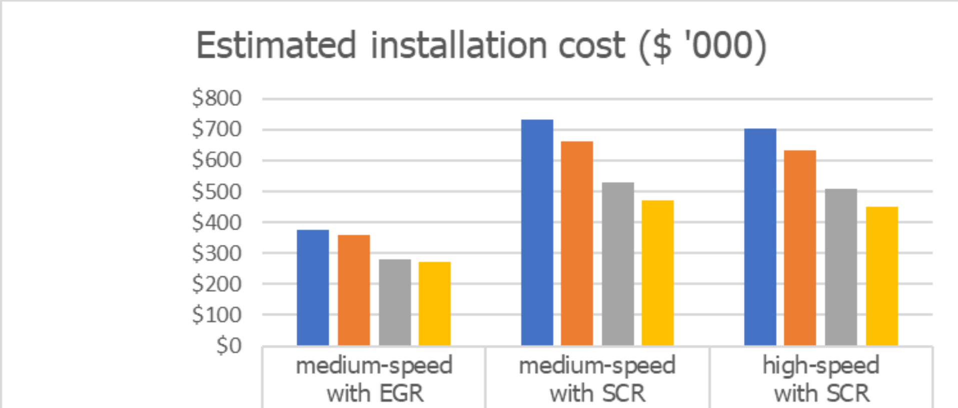
Table 6. Ambient heat rejection values, associated engine room ventilation requirements, and engine room ventilation fan cost

4.4 Summary of estimated installation cost

A summary of the total estimated installation costs for each region is shown in figure 4 [8]. The summary illustrates the effect of shipyard labor rates and estimated steel prices on the installation cost for each region. In all regions the configuration based on medium-speed engines with EGR technology has the lowest installation cost relative to the configuration based on medium-speed engines or high-speed engines with SCR technology.

The cost differences get smaller when the cost of steel and labor are reduced. For example, the configuration based on the medium-speed engine with EGR has a 47% ($330k) lower installation cost compared to the configuration based on high-speed engines with SCR and a 49% ($357k) lower installation cost compared to the configuration based on medium-speed engines with SCR in the Pacific Northwest region. Using the cost data for Asia, the configuration based on the medium-speed engine with EGR has a 40% ($179k) lower installation cost compared to the configuration based on high-speed engines with SCR and a 42% ($199k) lower installation cost compared to the configuration based on medium-speed engines with SCR.

The largest contributing factor to the installation cost difference between the configuration based on EGR technology and the configuration based on SCR after-treatment technology is the urea system. Within the urea system, the urea tank is the largest cost factor, driven by the stainless-steel material cost and fabrication. The total for the design, material and fabrication cost for the urea tank varied from $227k in the Pacific Northwest region to $132k in Asia.



	medium-speed with EGR	medium-speed with SCR	high-speed with SCR
Pacific Northwest	$374	$732	$705
Gulf Coast	$359	$660	$634
Europe	$278	$528	$508
Asia	$272	$471	$451

Figure 4. Summary of estimated installation costs

5. EGR operating benefits

Engines with EGR technology offer significant operating cost benefits over similar engines with SCR after-treatment technology due to the avoidance of cost for urea consumption, catalyst replacement and disposal, and maintenance on the urea tank, dosing system and SCR components. The total operating cost savings depends on the ship type, its duty cycle and the fuel, urea, and catalyst cost. The following case study is based on an ATB tug operating on the duty cycle depicted in table 7. Three different EPA T4 compliant propulsion engine configurations have been evaluated: (i) two medium-speed engines with Wabtec's EGR solution (each 2,500 bkW @ 1,000 rpm); (ii) two medium-speed engines with SCR after-treatment technology (each 2,600 bkW @ 900 rpm); (iii) two high-speed engines with SCR after-treatment technology (each 2,460 bkW @ 1,800 rpm).

Operating mode	Main engines power (bkW)	Aux gensets power (ekW)	Annual engine operating hours
Full load	5,000		500
85 % load	4,250		4,000
Maneuvering		1,000	1,500

Table 7. ATB tug operating profile for case study

The following assumptions were used to calculate cost for fuel, urea, SCR catalyst replacement and SCR maintenance:

- Fuel consumption is calculated based on published fuel consumption data for the respective engine model
- Urea consumption is calculated based on published urea consumption data for the respective engine model. If no published data was available, the consumption was calculated based on 13.5 g/kWh (40% urea solution), which is the stoichiometric quantity to reduce the NO_x content from an IMO II to an IMO III level
- The SCR catalyst replacement cost was calculated using a capex cost of $10,000 per installed MW and 15,000 operating hours change out interval
- The annual SCR system maintenance cost was estimated using $1 per installed kW
- Delivered fuel price of $0.65 per l
- Delivered urea (40% solution) price of $0.50 per l

The configuration based on the medium-speed engines with EGR technology showed the lowest average annual operating cost: 2% ($70k) lower than the configuration based on medium-speed engines with SCR technology and 8% ($260k) lower than the configuration based on high-speed engines with SCR technology. Refer to figure 5 for the results.

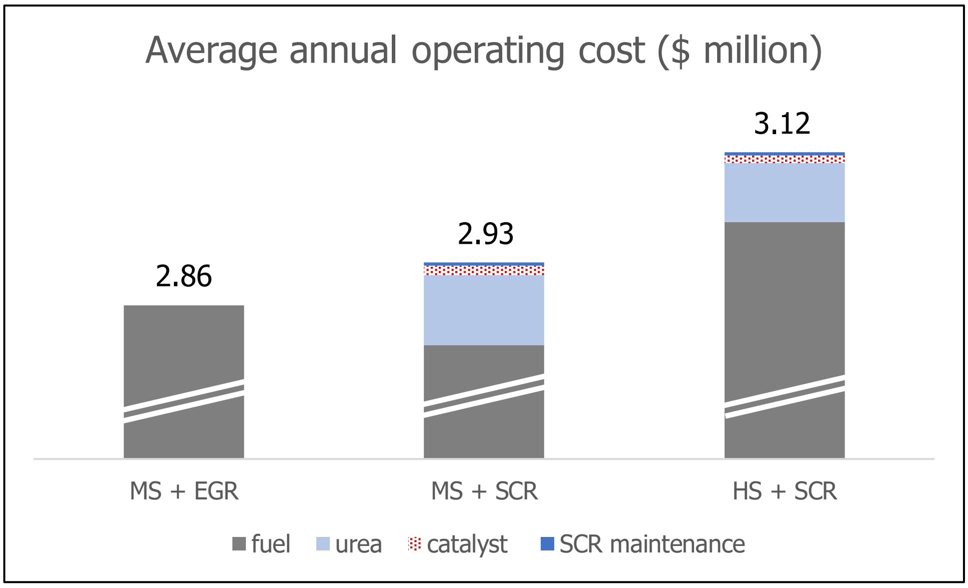


Figure 5. Estimated average annual operating cost

6. Field experience

The series of medium-speed engines with advance EGR technology went into commercial production at Wabtec in 2015. This breakthrough technology won “Best Technology for Cleaner Emissions” category at the 2018 Lloyd’s List Americas Awards. At the beginning of 2020, over 1200 of these engines are in service across heavy duty locomotive and marine applications. About 100 units have been delivered for marine applications and have accumulated over 600,000 operating hours, with the oldest engines exceeding 25,000 operating hours. Our references include, among others, ferries, offshore support vessels, expedition cruise vessels, dredgers, polar class research vessels, tugs, ATB tugs and push boats.

7. Conclusions

Wabtec has been first to launch a medium-speed marine diesel engine series which is certified to meet the IMO III and EPA T4 emissions standards by deploying advanced EGR technology, which minimizes the formation of NO_X during combustion as opposed to reducing NO_X in the exhaust gas through a series of chemical reactions in an after-treatment system. Engines with EGR technology offer significant benefits over engines with SCR after-treatment technology. Engines with EGR technology:

- Have 30% to 50% lower system weight
- Require 20% to 40% less space
- Have a 40% to 49% lower installation cost
- Have up to 8% lower operating expenses

Since commencing commercial production in 2015, the technology has been successfully rolled out with over 1,200 units in service across heavy duty locomotive and marine applications at the beginning of 2020. About 100 units have been delivered for marine applications and have accumulated over 600,000 operating hours, with the oldest engines exceeding 25,000 operating hours.

8. References

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Appendix A

Parameters used for U.S. Gulf Coast

General		
Labor rate	55	$/hr
Shipyard markup on procured equipment and margin on fabrication and installation work	15	%
Scrap allowance	20	%
Stainless steel labor premium	25	%
Structure		
Carbon steel structure labor	0.05	hrs/lb
Stainless steel labor	0.063	hrs/lb
Weld margin	3	%
Carbon steel plate and angles price per pound (cut and prepped)	2.70	$/lb
Stainless steel plate and angles price per pound (cut and prepped)	12.54	$/lb
5/16″ plate weight	12.76	lb/ft^2
3/8″ plate weight	15.32	lb/ft^2
1/2″ plate weight	20.42	lb/ft^2
Piping		
Carbon steel pipe labor	4.50	hrs/ft
Stainless steel pipe labor	5.63	hrs/ft
Valve installation	6.00	hrs/valve
Fitting installation	3.00	hrs/fitting
Carbon steel pipe (1″ and under)	5.00	$/ft
Stainless steel pipe (1″ and under)	17.00	$/ft
Stainless steel pipe (2″)	25.00	$/ft
Insulation	50.00	$\$/ft^2$
Carbon steel fittings	5.00	$/unit
Stainless steel fittings	20.00	$/unit
Stainless steel valve	200.00	$/unit
Carbon steel valve	70.00	$/unit