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Review Article

Comparison of turbo compounding technoligies on gasoline and diesel engines

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ABSTRACT

This paper presents a parametric study and comparison of turbocompound gasoline engine with diesel engine based on analysis done in previous papers. Turbocompounding is an important technique to recover waste heat from engine exhaust and reduce CO_2 emission, improving fuel economy.

By the time detected one of the biggest problems for IC engines is pollution. Downsizing studies are popular at the industry for the moments to get emission and fuel consumption decreased. Even if the racing industry gets involved in this trend having more efficient and more green racing vehicles is quite important for saving environment. Powertrain works with supercharged internal combustion engine by co-operation of two electric motors MGU-H (Motor-Generator Unit-Heat) and MGU-K (Motor-Generator Unit-Kinetic). It is also seen in passenger, light and heavy commercial vehicles with diesel engines using turbocompounding technology to decrease the pollution.

The present paper compares the outcomes which were shown in previous papers and demonstrate the better performance in terms of greenhouse effect and pollution as well as engine power generation performance.

Keywords: Turbocompound, energy analysis, hybrid powertrain, gasoline engine, diesel engine

1. Introduction

Technologies are used on a regular basis across the world. Vehicles are the most helpful technological innovations. The objective of previous inventions was to transport people more quickly from one location to another based on their needs, yet the number of vehicles on the road now is increasing all over the world. Because these technological vehicles include internal combustion engines. It is apparent that the pollution ratio is increasing day by day.

It is feasible to claim that nature is in a perilous scenario unless automobile manufacturers and consumers take measures or new green technology is introduced.

Hybrid technology is a significant technological advancement (basically usage of two types of energy at the same time on one vehicle: electric and ICE). Because of the electrical motor assistance for the thermal engine during key driving periods, this technological discovery offers us more efficient powertrain specifications and lower emission values.

Another significant advancement is turbocompound technology for the automobile sector, which allows us to obtain heat energy from exhaust gas, resulting in a compression different than intake air compression and hence a pure work output. Since 2014, turbocompound systems have been utilized in conjunction with hybrid technology in Formula One vehicles, and this scenario has been incorporated into FIA rules. Compounding is the process of combining more than one source to generate a single output. The exhaust gases are used to power a turbine, which is mechanically connected to the engine to generate a single output. Electric turbocompounding turns waste exhaust energy into shaft work, which is then electrically connected back to the engine.

This work intends to investigate and compare the behavior of hybrid-turbocompound systems using publications in current literature. Its implementation and outcomes on Formula One cars. In addition, there are comparisons between several turbines and compressors.

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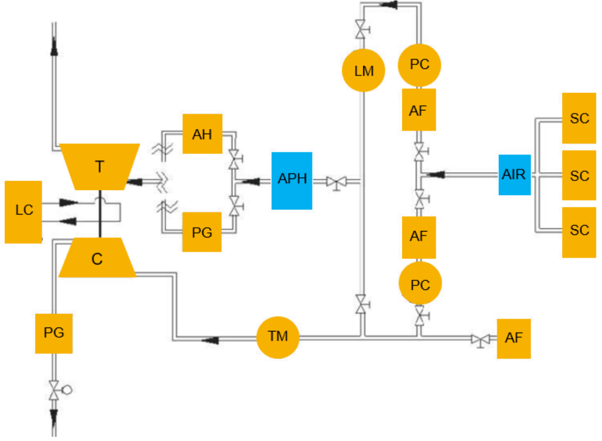
2. Turbocharge to Hybrid-Turbocompound

2.1. Experimental results on turbocharger performance

Here an experimental comparison will be conducted that was done by Internal Combustion Engines Group (ICEG) of the University of Genoa [1].



AF	Air Filter	LM	Laminar Flow Meter
AH	Air Heater	PC	Pressure Control
APH	Air Pre-Heater	PG	Pulse Generator
AR	Air Reservoir	SC	Screw Compressor
C	Compressor	T	Turbine
LC	Lubricating Circuit	TM	Thermal Mass Flow Meter

Fig. 1 Schematic of ICE [2].

It is depicted in Fig. 1 that the experimental system facilities constructed by Genoa University members. Based on the reference article, the following turbine and compressor specifications are provided:

For the current investigation, two turbines and one compressor have been found. Both turbines are nozzleless radial flow devices with a waste gate valve. The first turbine (Garrett GT2052, dubbed A) has a 47 mm rotor diameter and a TRIMt(The term trim expresses the area ratio between the inlet and the outlet of a radial flow wheel.) level of 0.72, while the second (IHI RHF3, called B) has a 33 mm rotor diameter and a TRIMt level of 0.81. The chosen compressor is a radial flow type (IHI RHF3) with an impeller diameter of about 40 mm [2].

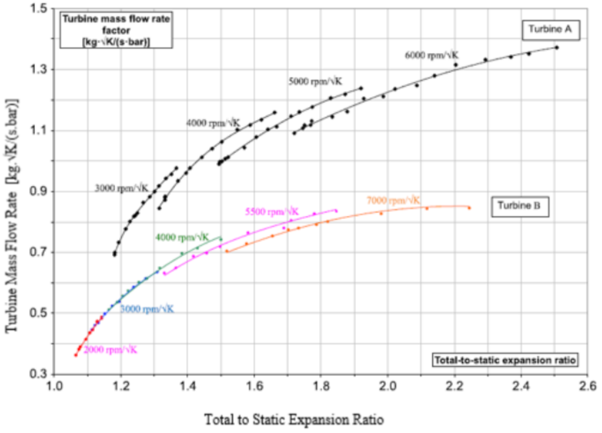


Fig. 2 Turbine Steady Flow Map [2].

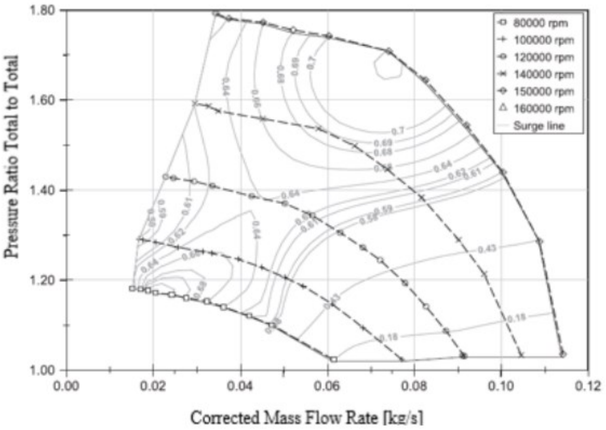


Fig. 3 Measured Compressor Steady Flow Map [2].

Referred turbine parameters:

$$Nt = \frac{n}{\sqrt{T_{T3}}} \tag{1}$$

Expansion Ratio (Total to Static) (-):

$$\varepsilon_{TS} = \frac{P_{T3}}{P_{S4}} \tag{2}$$

Mass Flow Rate Factor (kg √/(sbar)):

$$\varphi_T = \frac{Mt\,.\sqrt{T_{T3}}}{P_{T3}} \tag{3}$$

Table 1. Extract from the FIA F1 2014 Technical Regulation and Comparison with the Previous Rules (2011), [5].

	FI 2011	FI 2014
Thermal Engine		
Displacement	2.400cm^3	1.600 cm^3
Architecture	V8	V6
Max. Engine Rotational Speed	18.000 r/min	15.000 r/min
Supercharging	Forbidden	Exhaust has supercharger
Max. Fuel Flow Rate - Absolute	No Limit	100 kg/h
Max. Fuel Flow Rate – Related to the Engine Rotational Speed	No Limit	Q =0.009 n[r/min] +5.5 for n≤10 500 r/min
Electric System		
Energy Recovery	KERS (Kinetic Energy Recovery System)	MGU-K (Motor/Generator Unit - Kinetic) MGU-H (Motor/Generator Unit - Heat)
Storable Energy during the Race	No Limit	Energy released by MGU-K to Energy Storage System cannot overtake 2 MJ per lap
Max. Power for Electric Propulsion/Declaration	60 kW	120 kW
SOC (Battery State of Charge)		The difference between maximum and minimum SOC cannot overtake 4 MJ in each instant the vehicle is on the circuit
Time of Active (Acceleration) Electric Propulsion	6.67 s	No Limit

Compression Ratio (Total to Total) (-):

$$\beta_{TT} = \frac{P_{T2}}{P_{T1}} \quad (4)$$

Corrected Mass Flow Rate:

$$M_{cr} = \frac{M_C \cdot P_0 \cdot \sqrt{T_{T1}}}{P_{T1} \cdot \sqrt{T_0}} \quad (5)$$

Where $T_0 = 293.15\ K;\ P_0 = 0.981\ bar$

Isentropic Total to Total Efficiency (-):

$$\eta_{cTT} = \frac{T_{T2s} - T_{T1}}{T_{T2} - T_{T1}} \quad (6)$$

As a result, when we look at Fig. 2 and Fig. 3 above, we can see that the mass flow rate factor is more sensitive to the expansion ratio. (The rotational speed of the turbine with a constant waste-gate valve setting.) All speed curves can achieve a low turbine inlet temperature (400 K). The development of stable flow curves in vast operating ranges is required to decrease errors in the extrapolation approach used on simulation models [3].

2.2. The hybrid turbocompound system applied to the Formula 1

The FIA issued a new regulation in 2011 for 2014 automobiles. This legislation required the replacement of V8 engines with V6+turbocompound engines. That was also an improvement for the KERS system [4].

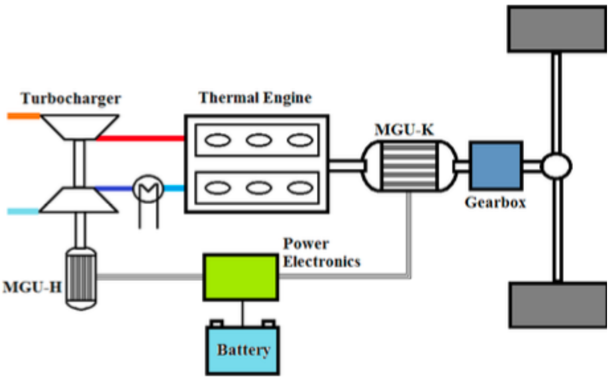


Fig.4 Powertrain Layout.

Table 1 clearly indicates the FIA's philosophical shift; formerly, constraints were imposed on vehicle power, but with the new regulations, restrictions were imposed on fuel flow rate. If one engine is competitive, it can deliver more power to all four wheels. This gives the team the advantage of green and efficient technologies.

Fig. 4 demonstrates a composition ICE provided with a turbocharger connected to electric machine (MGU-H), a second electric machine mounted on primary shaft (MGU-K). There is a typical battery for energy storage. All these systems have been connected to each other to ensure energy flow transfer between systems.

MGU-K reserves energy and charges the battery during the braking operation, MGU-H system keeps turbocharger at the same rpm that minimizes the turbo lag.

2.2.1. The system logic

Race configuration: SOC must be constant at the end of each lap.

- Full Load: MGU-K supplies energy to the wheel produced by MGU-H. Power flow from the battery to the MGU-K is restricted to the SOC threshold.
- Braking: MGU-K recovers vehicle kinetic energy, part of which is sent to MGU-H to retain the turbo at the same rpm, and the remaining energy is utilized to charge the battery.
- Release: Required energy for turbocharger group is taken from battery through MGU-H.
- Acceleration After a Release Phase: When the gas pedal is depressed, energy is drawn from the battery and given to the MGU-H. When the turbocharger group reaches the design speed conditions, MGU-H can save some energy from the turbo compounds and deliver it to MGU-K for acceleration contribution. SOC is crucial for this operation since it is feasible to acquire a bigger contribution from MGU-K by using more battery energy.
- Full Load: Maximum pedal angle, MGU-K provides the highest power value (120kW), using energy from both the battery and the MGU-H.
- Braking: Same as racing configuration.
- Release: The same as in racing mode.
- Acceleration after a release phase: When the MGU-H provides design speed for turbo components, it also provides all energy to the MGU-K and battery. As a result, MGU-K may achieve maximum power value during contributing.

2.3. The hybrid turbocompound system applied to the SCANIA truck

The MATLAB-based QSS (quasistatic simulation) [6] toolbox was used to simulate one engine with turbo-compounding and another with heat recovery and expansion via a steam expander. Both engine systems were subjected to a US Federal Heavy Duty Transient Test Cycle. Simulations results confirmed that the previous calculations, demonstrating that the heat recovery and expansion approach may save significant amounts of gasoline when compared to turbo-compounding.

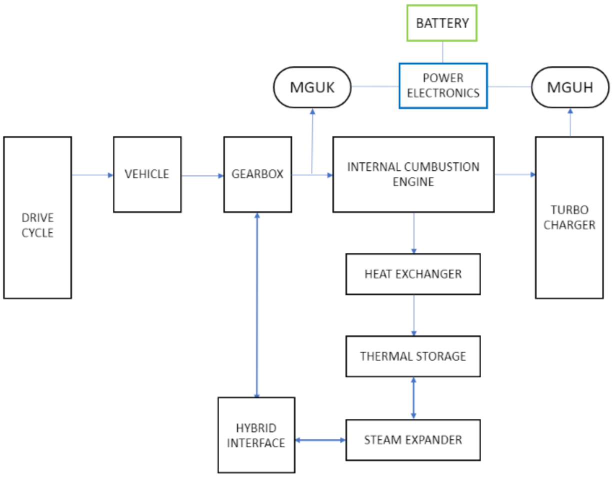


Fig.5 Powertrain Layout of Truck.

Table 2 demonstrates the power generated by each exhaust heat utilization system, the power generated by the internal combustion engine, and the fuel savings in each case. The vehicle model in QSS is depicted schematically in Fig. 5. QSS employs a backward facing one-dimensional calculating technique.

Table 2. Power Output Comparison for Truck with steam hybrid and turbo compound.

Simulation	Power (kW)
Truck with Caterpillar 3126 Engine	37.23
Truck with Steam Hybrid (Total Power)	37.23
Engine Power	34.3
Recovered Power	2.93
% Contribution	%7.8
Truck with Turbo Compound Hybrid (Total Power)	37.23
Engine Power	35.69
Recovered Power	1.54
% Contribution	%4.1

3. Results and Discussion

Based on experimental and bench studies of Genoa University here is given below comparisons between baseline and ETC (Electric Turbo Compound) case of configurations.

Dark Blue Colour Blocks: Percentage Variation of Total Brake Specific Fuel Consumption(BSFC) – Comparison Between Baseline and ETC-ICE at % 25 Load

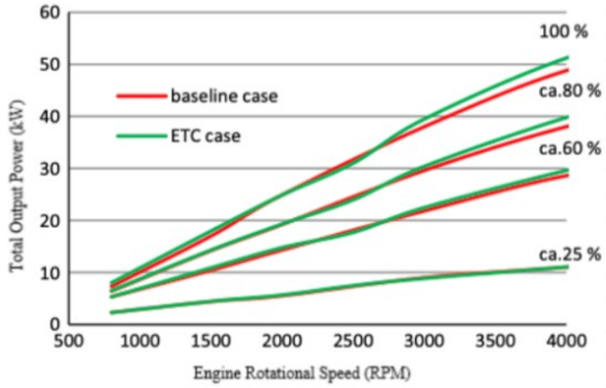


Fig.6 Total Output power [2].

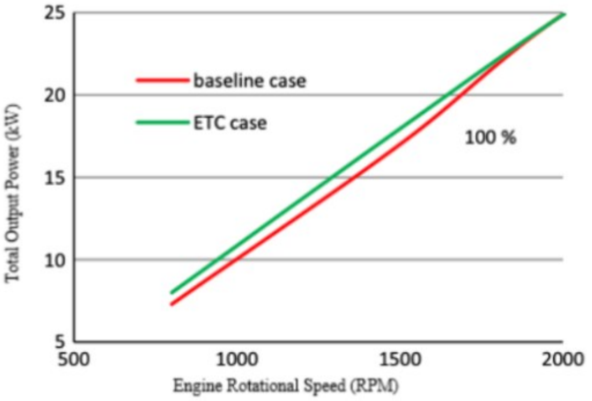


Fig 7. Comparison Between Baseline and ETC-ICE [2].

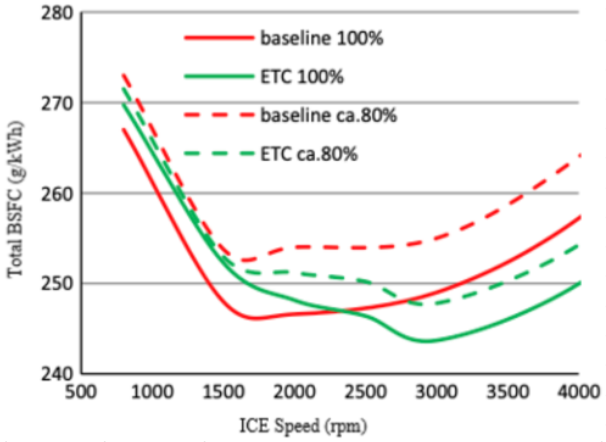


Fig 8. Total brake specific fuel consumption [2].

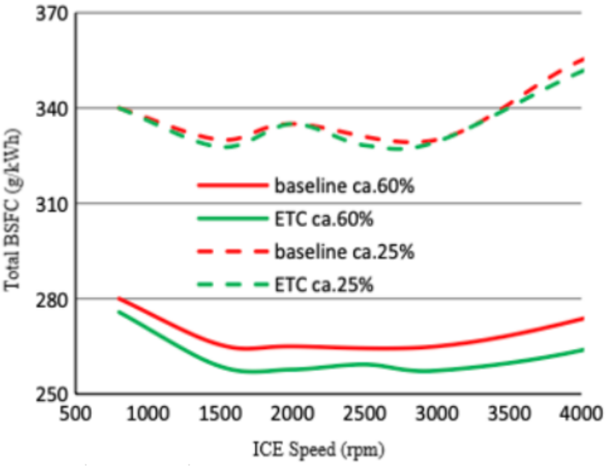


Fig. 9 Comparison between baseline and ETC-ICE at various loads [2].

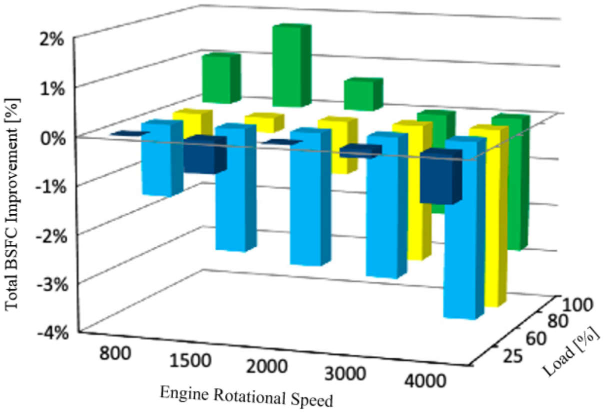


Fig.10 Percentage Variation of Total Brake Specific Fuel Consumption(BSFC) – Comparison Between Baseline and ETC-ICE at Various Loads [2].

Blue Colour Blocks: Percentage Variation of Total Brake Specific Fuel Consumption(BSFC) – Comparison Between Baseline and ETC-ICE at % 60

Yellow Colour Blocks: Percentage Variation of Total Brake Specific Fuel Consumption(BSFC) – Comparison Between Baseline and ETC-ICE at % 80 Load

Green Colour Blocks: Percentage Variation of Total Brake Specific Fuel Consumption(BSFC) – Comparison Between Baseline and ETC-ICE at % 100 Load

Fig. 6 and fig. 7 illustrate total power vs. reasonable speed to compare the baseline situation with the ETC-fitted ICE. Total power is defined as the combination of engine power and electrical power with 100% electric drive efficiency. As can be seen, there is a minor increase in total power at mid-low ICE rotational speed levels, which grows with ICE speed and excess power recovered by the electrical machine [7].

In Fig. 8 and Fig. 9, the electric drive serves as a motor below 2500 rpm, enabling the turbocharger to generate the needed boost pressure. Over 2500 rpm, the electric drive acts as a generator, “braking” the turbocharger and collects the turbine's energy surplus. Differences in engine efficiency with and without ETC is better stressed in Fig.10, where the percantege variation of baseline BSFC is compared with total BSFC of the ETC-fitted ICE at same operating conditions.

ETC system can be used in a hybrid powertrain as if it is used in F1 at the moment. The Machine of ETC system has to convert exhaust energy into electrical power and this mechanism should be connected directly to the shaft of the standard

TC group. Besides alternator is connected to the ICE (interface with DC) through a rectifier bridge so that this feeds auxiliary loads. Auxiliary loads are kept the same.

Energy transfer between ETC and alternator pully should be double directional so that rectifier bridge could be replaced with bidirectional converter.

Results of turbocharger;(MGU-H model)

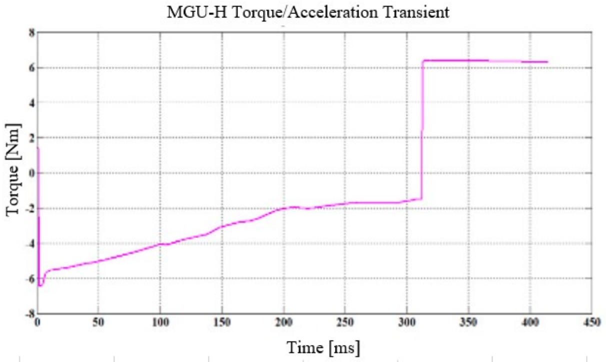


Fig.11 MGU-H torque during acceleration transient [5].

Previously MGU-H torque function named as in function during acceleration phase. Fig. 11 shows that turbo lag assumption 0,3 s. and shaft initial rotation speed 80 000 r/min. Electric machine passes from torque supplying to torque absorption. As soon as system reaches 120 000 r/min. mode is being switched from motor to generator.

The power of the MGU-H machine is depicted in Fig. 12 as a function of time. The graphs demonstrate that for a speed of 50 000 r/min, only about 12 kW is needed to maintain the turbocharger group at the desired speed during the braking and release phases, while for a speed of 110 000 r/min, about 67 kW is needed.

Summarization of racing and qualifying configurations results;

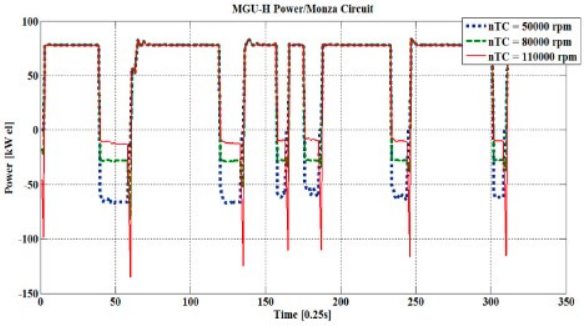


Fig.12 Power of the MGU-H in the Monza circuit for different fall speeds of the turbocharger [5].

Fig. 12 represents power changing of MGU-H machine in time so that it shows required power at the desired speed during braking and releasing phases lower from 50 000 r/min speed (about 12 kW), when speed is 100 000 r/min it is around 67 kW but the diagram shows us that re-accelerating power requirement rises up to 130 kW for 50 000 r/min case. (0,3 s turbo-lag). The 130 kW is being supplied by the battery.

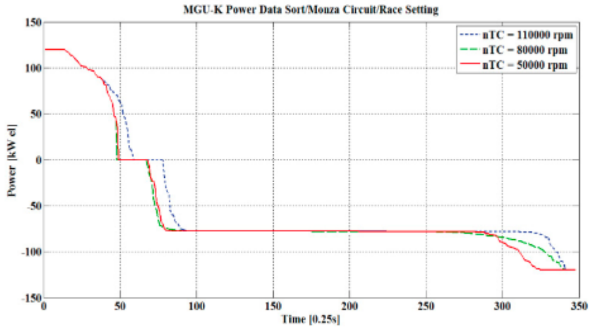


Fig.13 MGU-K power duration curve [5].

The Fig. 13 curves are related with MGU-K duty cycle for the three values of turbocharger speed fall in braking and release operations. Curves represent the amount of the time for power supplying or absorbing mechanisms. It is strictly connected with stress on component and to the energy dissipated by Joule effect. This data is useful for a decision about the sizing of cooling system and electric components.

As it is shown above in fig. 14, 50 000 r/min case the MGU-K supplies its maximum power of 120 kW for a rather long time during the lap, respect to the 80 000 and 120 000 r/min cases.

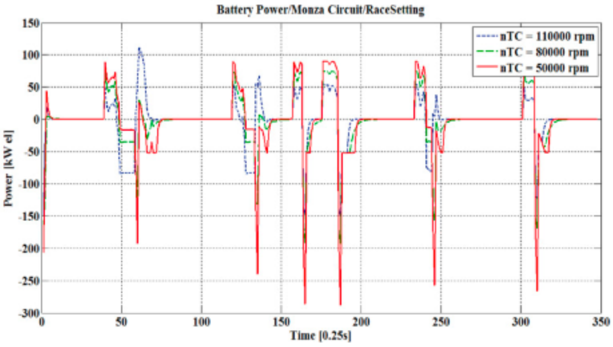


Fig.14 Battery power, history with time for different fall speeds of the turbocharger in race setting [5].

Based on fig. 14 it is apparently clear that battery is getting under big stress during racing conditions. For the 50 000 r/min case negative peaks around 270 kW because battery needs to send energy for MGU-H and MGU-K.

Qualifying conditions;

FIA permits to use only one size of the battery for qualifying and racing configurations but in qualifying section it is free to consume all capacity of electrical support and have faster lap speeds. So that it means that battery is under massive stress for this configuration.

In qualifying conditions, the absolute value of the average battery power is higher than race conditions. For example, in the 50 000 r/min case the average power value is 48.9 kW; in the 80 000 r/min case it is 46.1 kW; for the 110 000 r/min it is 43.0 kW.

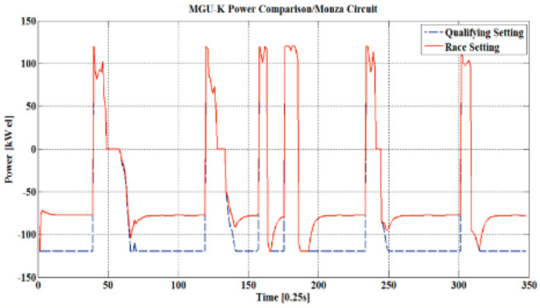


Fig.15 MGU-K power: comparison between race and qualifying settings [5].

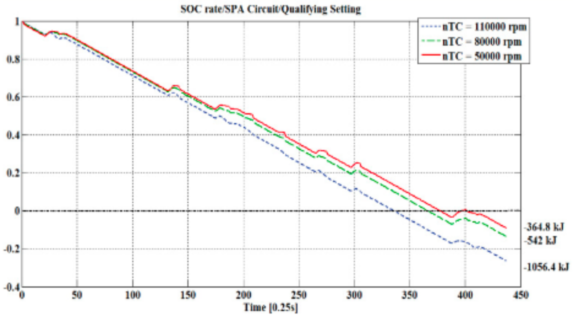


Fig.16 SOC in qualifying for the Spa-Francorchamps circuit [5]

Fig. 15 shows that for the Monza circuit MGU-K is supplying maximum power as 120 kW almost all the full load phases.

4 MJ of stored energy is allowed condition by FIA and as it is expected 4 MJ of stored energy is consumed before the lap is finished as shown in Fig. 16. The best configuration is 50 000 r/min that provides us SOC for all over the lap.

Table 3 shows the power generated by each bottoming cycle. When compared to turbo-compounding, the exhaust heat utilization secondary fluid power system can produce at least two percentage points more power. Based on modeling results, exhaust heat utilization steam hybrids can save 20% or more on gasoline compared to turbo-compounding, which only saves about 2%. (Table 2). How a 7.8% increase in power results in a 22% increase in fuel efficiency raises the question. This can be explained in terms of the exhaust heat secondary fluid power cycle's capacity to store heat. A heat recovery and expansion cycle is superior to a turbo-compounding cycle in terms of how it "responds" to temperature changes. The extra energy lost while the engine is severely loaded is collected and stored in the secondary fluid reservoir. The cycle's secondary fluid (in this case, steam) reservoir serves as an energy source.

Table 3. Power Output Comparison for Truck with Steam Hybrid and Turbo Compound.

Simulation	**Power (kW)**
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Engine Power	35.69
Recovered Power	1.54
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4. Conclusion

This essay aims to explain how turbocompound systems are employed in the most recent automotive innovations, including trucks and racing automobiles. In light of the cited articles, hybrid turbocompound systems for F1 cars and trucks are considered to be at the extreme end of the application spectrum.

Hybrid electric vehicles [8,9], the performance and fuel efficiency of hybrid electric vehicles may unquestionably be improved by turbocharging with MGU-H. The lack of turbo-lag during accelerations and the flat, high, low, and middle speed torque are the main benefits. There are several places on the map where waste energy is recovered, either for the exhaust energy that would otherwise be wasted at high loads and speeds or during decelerations, although the gains are often rather small.

However due to cost and benefit balance application of F1 technology on road vehicles may not be the most economically efficient decision yet these days, hybrid turbocompound technology is now being used in commercial automobiles, trucks, buses, and railroads. With the help of this technology, we are able to reserve some energy and charge batteries while also benefiting from the ability to consume certain exhaust gases. In addition to using the energy generated by electric machinery, turbocompound material can support turbo systems. We can finally achieve lower pollutants and fuel consumption.

CRediT authorship contribution statement

Esra Asi Öztaş: Writing - original draft, Investigation, Visualization, Supervision, Conceptualization, Methodology, Software, Formal analysis. **Berkay Genç:** Investigation, Supervision, Writing – review & editing. Funding acquisition. **Serdar Güler:** Investigation, Conceptualization, Supervision.

Declaration of Competing Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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