Assessment of the effect of low viscosity oils usage on a light duty diesel engine fuel consumption in stationary and transient conditions.

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Abstract

Regarding the global warming due CO_2 emissions, the crude oil depletion and its corresponding rising prices, OEMs are exploring different solutions to increase the internal combustion engine efficiency, among which, the use of Low Viscosity Oils (LVO) represents one attractive cost-effective way to accomplish this goal. Reported in terms of fuel consumption, the effect of LVO are round 2%, depending on the test conditions, especially if the test has taken place in laboratory or "on road" conditions. This study presents the fuel consumption beneffits of a commercial 5W20, compared against higher SAE grade oils, on a light duty diesel engine, when it is running under motored test, stationary fired test and the New European Driving Cycle (NEDC).

Keywords: Low Viscosity Oils, Fuel consumption, CO_2 reduction, Engine efficiency.

Highlights

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- The use of low viscosity oils (LVO) leaded to lower engine fuel consumption.

- SAE 5W20 lubricant diminished the friction losses in the engine.

- At low engine speeds and loads the improvement effect of low viscosity lubricants is more noticeable.

- The “cold start” enhance the low viscosity lubricants effect on fuel consumption.

1. Introduction

Is a well-known fact that Green House Gases (GHG) emissions from the combustion process which takes place during the working cycle of the Internal Combustion Engines (ICE) contributes significantly to global warming[1–3]. Additionally, the sustained raising price of the fossil fuels and crude oil's depletion increases the necessity to improve the ICE efficiency [4–6]. Furthermore, fuel economy and CO_2 regulations have been imposed in several countries in the recent years both for light duty and heavy duty segments and is expected that these regulations will be more severe in the future[7, 8].

To face these challenges, OEM's have been working on diverse techniques to reduce fuel consumption and CO_2 emissions which include; direct injection, variable valve actuation, downsizing, stop-start engines, the use of bio-fuels, and so on. Among these proposed powertrain efficiency enhancing techniques, the use of Low Viscosity Oils (LVO) has been studied as a cost-effective way to reduce fuel consumption, based on the principle that the less viscous the lubricant oil is, the less engine power is required to reach some specific operational conditions[9–11]. Tribologically this assumption is valid when the lubricated interface is under a hydrodynamic regime, which takes place when the lubricant layer thickness is large enough to prevent contact between the moving parts, being the lubricant's inner shear strength the only resistance which goes against the relative movement. Consequently by reducing the oil's viscosity, the magnitude of this resistance tend to diminish leading to reduced fuel consumption. Nonetheless, the viscosity reduction approach must be done carefully when engine oil is being formulated cause less viscosity implies lesser oil thickness, moving the lubrication regimes towards mixed and boundary zones where wear could be increased. It has to be mentioned that the use of LVO does not require additional engine modifications, hence the cost-benefit ratio is wider than for other techniques.

However, the reported benefits of fuel consumption reduction of LVO, in terms of percentage, vary significantly both for the light and the heavy duty segment, ranging from 0,5% to 3,5% depending on many factors like the test nature (i.e. chassis dyno, engine bench test fired, engine test motored, stripping test and so on), engine's constructive characteristics (i.e. valve train system, number of cylinders, injection system, materials, surface finish, fuel, so on), SAE oil viscosity grades used, etc. Historically, the reduction on fuel consumption is greatest when test bench and dynamometer test are performed compared with the results given by "on road" tests, these differences between methodologies can easily be explained by the additional losses that a given vehicle performing an equivalent driving cycle has to overcome (e.g. aerodynamic, rolling resistance, so on).

On the other hand a vehicle performing the same driving cycle on a bench test dynamometer which has not to carry these losses will achieve the cycle profile requiring less power and thus the effect of LVO will be more noticeable.

The target of the study reported in this paper was to explore the potential of using a commercial LVO 5W20 SAE grade oil on a light duty diesel engine's friction and fuel consumption. As a reference baseline, a 5W30 SAE grade oil with the same additive package as the 5W20 was used. For the fired stationary test a 15W40 SAE grade commercial oil with a similar additive package was used as well.

2. Experimental setup

A high pressure direct injection, 4 cylinder, 1.6 l, turbo diesel engine, which meets Euro 5 regulations for light duty vehicles was employed. The engine specifications and the lubricants main characteristics are shown in Table 1 and Table 2.

Engine	
Displacement	1560cc
Cylinders	4 in line
Valves	2 Valves per cylinder
Max power	82 kW at 3600 rpm
Max torque	280 Nm at 1750 rpm
Turbo	Variable geometry
Emissions control	EGR, particle trap

Table 1. Engine main characteristics.

	Oil A	Oil B	Oil C
SAE Viscosity grade	5W30	5W20	15W40
Base oil	API G-III	API G-III	API G-I
CCS viscosity (cP)	5120@-30°C	4519@-30°C	4878@-20 °C
Kinematic viscosity at 40°C (cSt)	53	45	107
Kinematic viscosity at 100°C (cSt)	9,7	9,0	14,6
HTHS al 150°C (cP)	2,9	2,8	3,7

Table 2. Lubricants main characteristics.

The engine was coupled with a Schenck-Pegasus dynamometer controlling online engine torque and speed. The control software used was a CMT "in-house" development named SAMARUC, able to program the driving condition of the vehicle. By means of this software the New European Driving Cycle (NEDC) was programmed as a time sequence for gears and vehicle speeds taking into account the vehicle features and current driving skills. In order to register engine's parameters, Engine Control Unit (ECU) was totally opened and the engine setting maps could be calibrated with the ETAS INCA Software. The engine test bed was equipped with a series of temperature, pressure and air mass flow sensors in order to control the engine precisely. Fuel consumption was measured by means of a fuel gravimetric system, the AVL 733S Dynamic fuel meter. It consists of a measuring vessel filled with fuel suspended on a balance system. Fuel consumption values were then obtained by calculating the vessel's time related weight loss. As the response time of this system was too long for the dynamic study, a calibration of the fuel consumption signal provided by the ECU was performed in steady state. This ECU signal was used as a secondary fuel consumption measurement.

In this engine setup an external circuit to control coolant temperatures was set. However, the set up had not an external circuit to control oil temperatures. Oil temperatures in this case were controlled varying the coolant flux in the engine intercooler, having reasonable results for the most of the test performed with the setup. Further discussions over the effectiveness of this setup and its incidence on every test will take place in the results section of this manuscript.

3. Friction and fuel consumption test procedures

As it was mentioned before, the goal of this study is to assess the effect of lubricant viscosity on fuel consumption in light duty vehicle engines. To do so, an initial motored test focused on determining the real potential of the LVO to reduce the engine friction when the engine works on different engine speeds was conducted. This test intended to measure the torque differences required by the dynamometer to reach several engine speeds, being this a clear indicator of possible changes in mechanical losses. Then a screening over the engine's functional map was made by means of a stationary fired test. The purpose of this second test is to report the engine operating points where potential fuel consumption reduction due LVO use are more noticeable. In this stationary fired test, BSFC obtained for each point with every oil is used as a comparison parameter. Finally, a transient cycle test was performed in order to address the effect of LVO when the engine works under real driving conditions. In this final test, the comparison was made taking into account the overall fuel mass consumed. These three methods are described largely in the following paragraphs.

3.1. Stationary motored test

This procedure consists in measure the required torque used by the dynamometer to motor the engine at certain speed. One objection to this method is the fact that in absence of combustion the entirely variables which affect the engine's performance are misplaced (i.e. temperature profiles, air in cylinder pressure, parts strain, etc.). To get a more accurate approximation to the engine's operating conditions, motored tests should be performed after the engine has been working under fired conditions and controlling coolant and oil temperatures[12].

Although it does not simulate the engine's working conditions due its unfired nature it has been widely used as an indicator of the engine frictional behaviour. For this test in particular, torque measures were taken for seven engine speeds ranging from 1000 rpm to 4000 rpm, every 500 rpm.

3.2. Stationary fired test

The test under stationary fired condition took place in order to address the relative impact and possible fuel consumption benefit of LVO in specific stationary points of the engine's map. The stationary test offers a significant control level over the engine's variables (i.e. temperatures, engine's speed, among others), making easier to address the effect of any particular change of these variables in engine's performance. A 12 point screening on the engine's working map was planned to identify the working zones with more potential for fuel consumption reduction. The method employed consisted in compare the final torque output for each point at "iso-consumption" conditions for the three levels of viscosity given by the different oils and having oil A as the baseline. Each single point measurement has involved a three time repetition, every one of them being the average of engine's fuel consumption values on a 30 s period. To complete the test under "iso-consumption" conditions an initial round of measurements was made with oil A and using as inputs for each points the values given in Figure 1 and Table 3.

Point	Load (%)	Speed (rpm)
1	25	4000
2	75	1000
3	75	2000
4	25	1000
5	75	3000
6	50	3000
7	25	1000
8	50	4000
9	50	2000
10	25	2000
11	75	4000
12	25	3000

Table 3. Stationary fired test points.

Output parameters as fuel flow rate, EGR %, GVT %, manifold inlet air pressure, and SOI were registered for each of the 12 points. After flushing oil A and replacing it with the candidate oil (oil B or C), the 12 points were measured again fixing this time, engine speed and fuel flow rate measured with oil A as inputs. Values of EGR%, GVT %, manifold air pressure and SOI were controlled to assure similar combustion conditions.

Finally, resulting torque registered for each point and oil was used as the main source to compare the BSFC differences leaded by the use of the different lubricant oils. This aproximation could give more precise results than the "iso-power" like test, where the engine could deliver the same power working in different points of its funtional map.

3.3. NEDC test

The NEDC test was planned mainly to bear out the gain on efficiency leaded by the LVO when the engine operates on transient conditions. This approach gives the closest approximation of real "on road" benefit in fuel consumption that could be reached by the use of LVO, being this value the most important for OEM and end-users.

Also known as the MGEV-A, this cycle was used in the European Union to test vehicles emissions and fuel economy behaviour. Originally developed to be performed on a chassis dynamometer, the cycle emulates the typical driving conditions of a light duty vehicle in Europe, with vehicle velocity profiles for both urban and extra urban driving conditions, with a total duration of 1200 s. At the beginning of the test, the room, the engine coolant and oil temperature should be between 20°C and 30°C. The first part of the cycle is known as UDC (Urban Driving Cycle) consisting of four ECE-15 segments of 200 s. In the other hand the last 400 s of the driving cycles simulates highway conditions, and is known as the EUDC (Extra Urban Driving Cycle), where the vehicle can reach 120 km/h. The NEDC could be simulated as well on an engine test bed, controlling the engine's speed and load. As these values were used to perform the NEDC it could be said that the comparison between the two oils is made under "iso-power" conditions.

4. Results and analysis

The results obtained for the three different tests are shown following. As a general convention, the differences of friction and fuel consumption measured are presented in this document as a percentage difference between the 5W30 SAE grade reference oil and candidate oils. The reference oil is taken as the baseline; in accordance, positive percentage values indicate reductions in friction and fuel consumption when using the candidate oil, and negative values indicate an increase in the fuel consumption due the use of the candidate oil.

4.1. Motored friction test

As it can be seen in Figure 2 and Table 4, the use of a less viscous oil led to significant lower motor torque values. The friction data from this test presented an increasing trend paired with engine speed, with a local peak at 1500 rpm. The unusual shape for both oils could be explained by an irregular behaviour of pumping losses detected on these engine speeds which lead to indicated pressure increase.

	Engine speed (rpm)						
	1000	1500	2000	2500	3000	3500	4000
Oil A	22,5	28,3	26,4	32,0	37,2	44,1	52,9
Oil B	19,7	26,3	25,9	29,0	32,8	37,8	45,5
Diff (%)	12,4	7,1	1,9	9,5	11,7	14,3	14,0

Table 4. Torque (Nm) required to reach different engine speeds (rpm).

From there to 4000 rpm the data shows the typical behaviour of the hydrodynamic regime, with rising values of required torque as the engine speed was increasing. In the same way, the difference of required torque in percentage between oil A and B increased as the engine was reaching higher velocities as it can be seen in Figure 3. The effect of the oil viscosity on torque required is clearly observed. When the engine speed increases in absence of combustion, the hydrodynamic lubrication regime on the shaft bearings and during the displacement of piston ring in the inner engine block rules over the valve train's mixed regime, hence allowing the less viscous oil to show its lower inner shear resistance as the engine speed increases. It has to be taking into account that as velocity increases the required torque rises for both oil A and B. Despite of the load differences which could be found against a fired test, the motored test confirms the LVO potential when the engine works at medium-high speeds and low loads.

(rpm)	5W20	5W30
1000	60,7	60,8
1500	65,4	65,1
2000	65,0	64,9
2500	67,7	65,0
3000	71,7	65,0
3500	76,3	68,6
4000	81,1	73,2

Table 5. Average oil temperatures in °C at given engine speeds for Oil A and Oil B during motored test.

4.2. Stationary fired screening test results

For this test, measures with a third oil, more viscous than oil A and oil B took place. The properties of this oil (Oil C), could be seen in Table 2. The results of this test revealed a high correlation between the oil viscosity and the BSFC when the engine works at speeds under 2000 rpm and low loads. Decreases as high as 4% in BSFC when 15W40 is compared to 5W30 as baseline can be found at low engine speeds and low load. Nonetheless, as the load increases, the effect of LVO changes, leading even to an increase on fuel consumption especially at low engine speeds (e.g. as it can be seen in the Table 6. BSFC can rise when LVO are used at low speeds and high loads). These result are consistent with studies made before where the influence of load on the tribological conditions where studied[13]. Apparently this trend is mitigated as the engine speed reach values over 2000 rpm, as it could be expected from the lubrication theory.

As it was mentioned before, the effect of LVO on fuel consumption could be clearly seen in the Figure 4 where for the three different fuel mass flow values (related to the load percentage measured with the baseline oil) the BSFC increases as the oil viscosity increases too. It can be seen as well, the reduction of this effect when the fuel mass flow is maximum.

Load	25(%)	50(%)	75(%)
5W30-15W40	-4,44	-3,71	1,02

Table 6. Differences of fuel consumption at 1000 rpm.

For speeds of 2000 rpm and over the load increase masks the benefit on fuel consumption of the less viscous oil, and in some cases overtaking the BSFC value of the most viscous one.

Load	25(%)	50(%)	75(%)
5W30-15W40	-3,42	-1,77	-0,24

Table 7. Differences of fuel consumption at 2000 rpm.

A loss of the effect of LVO over fuel consumption when the engine load was over the 50% was observed. It could be explained by using the Stribeck theory [14], where an increase in load could lead to a possible increase in the friction coefficient, due the change of the lubrication regime from hydrodynamic to mixed or boundary. The weight of the load increase over the friction coefficient in a particular engine will vary depending on its constructive and functional design and it will be probably different from one to another engine (i.e. the results concerning this study may not be quantitatively directly extrapolated to other engines).

Load	25(%)	50(%)	75(%)
5W30-15W40	-2,06	-1,24	-1,07

Table 8. Differences of fuel consumption at 3000 rpm.

The ambient temperature, pressure and humidity in the test cell during the fired stationary test performed for the three oils can be seen on table 9.

Oil tested	Temperature [°C]	Pressure [mbar]	Humidity [%]
5W30	32,8	1023	31,8
15W40	33,8	1022	30,9

Table 9. Test cell ambient conditions when tests took place with the three different oils were performed.

Load	25(%)	50(%)	75(%)
5W30-15W40	-0,27	-1,41	-1,05

Table 10. Differences of fuel consumption at 4000 rpm.

In Figure 7, shows the trend of BSFC improvement when load is increasing for different engine speeds. The graph shows the linear regression for each data set, all of them with good R^2 values (over 0,8) except for 4000 rpm where the correlation was very low (0,45) due an estrange value at 4000 rpm and 25% of load, which could be a possible measurement error.

As it can be seen the lower the speed, greater the influence that load has over the BSFC improvement. As the engine speed increases the relative effect of load variation on the BSFC improvement decreases. It can be said that at lower engine speeds a greater effect of LVO on fuel consumption could be seen at low loads but this effect rapidly disappears as the load increases. In the other hand, with higher engine speed the effect of LVO on fuel consumption may could not achieve greater values but it can be maintained over the all range of engine loads. The same results can be seen in Figure 8. It is noticeable that there is an average 1,64% of improvement on the BSFC over the test 12 points when the engine is using 5W30 oil compared against the BSFC when the engine was using 15W40.

4.3. NEDC test

Test results indicate that 5W20 SAE grade oil can reduce the fuel consumption around 1,7% compared with a 5W30 SAE grade as it can be seen in Table 11.

In accordance, Figure 9 shows the accumulate fuel consumption average for each oil during the NEDC cycle period. It can be clearly seen that a major portion of fuel consumption has taken place during the last 400 s of the cycle when the EUDC takes place. However during this cycle, the decrease of fuel consumption is the lowest compared to the other sub-cycles as can be seen in Table 12.

Load	Cycles Repetitions	Average F.C. (g)	Standard deviation	F.C. decrease (%)
A	4	426,55	5,61	
B	4	419,38	9,68	1,67

Table 11. NEDC fuel consumption results.

It is noticeable that fuel consumption reduction takes place mainly in the UDC cycles and then the improvement tends to decline, especially during the EUDC.

Sub-Cycle	Oil A (g)	Oil B (g)	Difference (%)
UDC1	49,99	48,50	2,98
UDC2	45,57	44,18	3,0
UDC3	42,54	41,50	2,45
UDC4	41,34	40,42	2,23
EUDC	247,11	245,83	0,52

Table 12.Fuel consumption differences in percentage for each of the NEDC sub-cycles.

It has to be taken into account that NEDC cycle simulates the so called cold start (between 20°C and 30°C), that means that the most viscous lubricant will give more resistance leading to higher fuel consumption values. In addition, it has to be stated that other engine variables increase the effect of higher fuel consumption while the engine is reaching the optimal operational temperatures. An approximation of oil's temperature trend (measured at the engine sump) during the NEDC performance can be seen in Figure 10, where the instant temperature for every UDC cycle is plotted both for oil A and oil B. It can be clearly seen that oil temperature increase is slightly minor for oil B which could be interpreted as an indicator of less friction when this less viscous oil is used. Additional analysis on NEDC average fuel consumption data confirm the correlation between the oil temperature and fuel consumption. In Figure 11 a Box-Whisker diagram show the trend of fuel consumption during the NEDC cycle in a clear way. In order to relate these variables better, the average temperature and the fuel consumption average of UDC 1 were taken as a baseline to calculate the relative increment or decrease of these variables during the subsequent UDC cycles. These differentials exhibit a good linear correlation ($R^2 = 96,13$) as can be seen in Figure 12. These data are relevant when the following European driving patterns are taken into account[15]:

- The average trips during the day are around 2,5.
- Nearly 40 % of the trips take place before noon.
- Average commuting distance is around 18 km.
- Average duration of trips takes between 20 and 30 minutes.
- Car is used around 1,5 hours per day. The active parking[1] is around 6,5 hours per day.

[1]'Active and inactive parking refers to the time the car is parked between trips during the day and the time the car spends parked until the next day use respectively.'

- The inactive parking is around 16 hours per day.

Taking into account the results from the stationary fired test, and comparing them to the NEDC tests results it can be clearly seen that engine loads and speed of the typical urban driving (see Figure 8 and Figure 13) are those where the stationary fired test reported the greatest fuel consumption reduction when the low viscosity lubricants were used, being this reduction as high as 4% when 15W40 and 5W30 are compared in low speeds and low loads.

Another good concordance between stationary fired and the NEDC tests results can be observed in the Figure 14, where the cumulative fuel consumption difference in grams between 5W30 cycles and 5W20 cycles is plotted for the complete duration of the NEDC. Alongside the engine speed over the NEDC cycle is plotted as well in order to make visible the relation between the engine speed with the effect of oil viscosity on fuel consumption.

As it can be observed, the cumulative difference increases in periods where engine speed and torque (not plotted) are low, mainly during the urban segment of the cycle, whereas during the extraurban segment this cumulative difference tends to diminish (being this an indicator of higher fuel consumption with the 5W20 oil than with the 5W30 oil), especially when medium to high loads are being reached.

5. Conclusions

As it has been observed, low viscosity oils (LVO) can be considered as a key player in the fight for fuel consumption reduction in the automotive sector.

This reduction could be significant especially when the engine work at low loads. This can be supported by the NEDC cycle tests results (NEDC cycle operates at low speeds and loads since it simulates urban driving conditions in most of its length). In the same way stationary fired points exhibited the same behaviour, however LVO reported higher BSFC when load was higher than 50%. Motored test exposed the potential of friction reduction when LVO are used, mainly when the engine works at hydrodynamic regimes.

The potential contribution to fuel consumption reduction rarely will exceed more than 2%-3% in transient conditions, attending factors such as: engine design, engines displacement, materials used, and so on.

As it was observed, the effect of LVO has to be considered as well in the cold start process. Taking into account the typical daily light duty vehicles use in Europe (less than 80 km/day[2], an average of 6,5 hours parked during the day, and 16 hours during the night) it can represent a good advantage on fuel consumption reduction.

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[2]In Spain, other countries, like UK, could have a reduced rate, around 40%.

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Figure captions

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- Figure 14. Fuel mass accrued difference between Oil A and Oil B and engine speed during NEDC cycle.

FIG1 Color

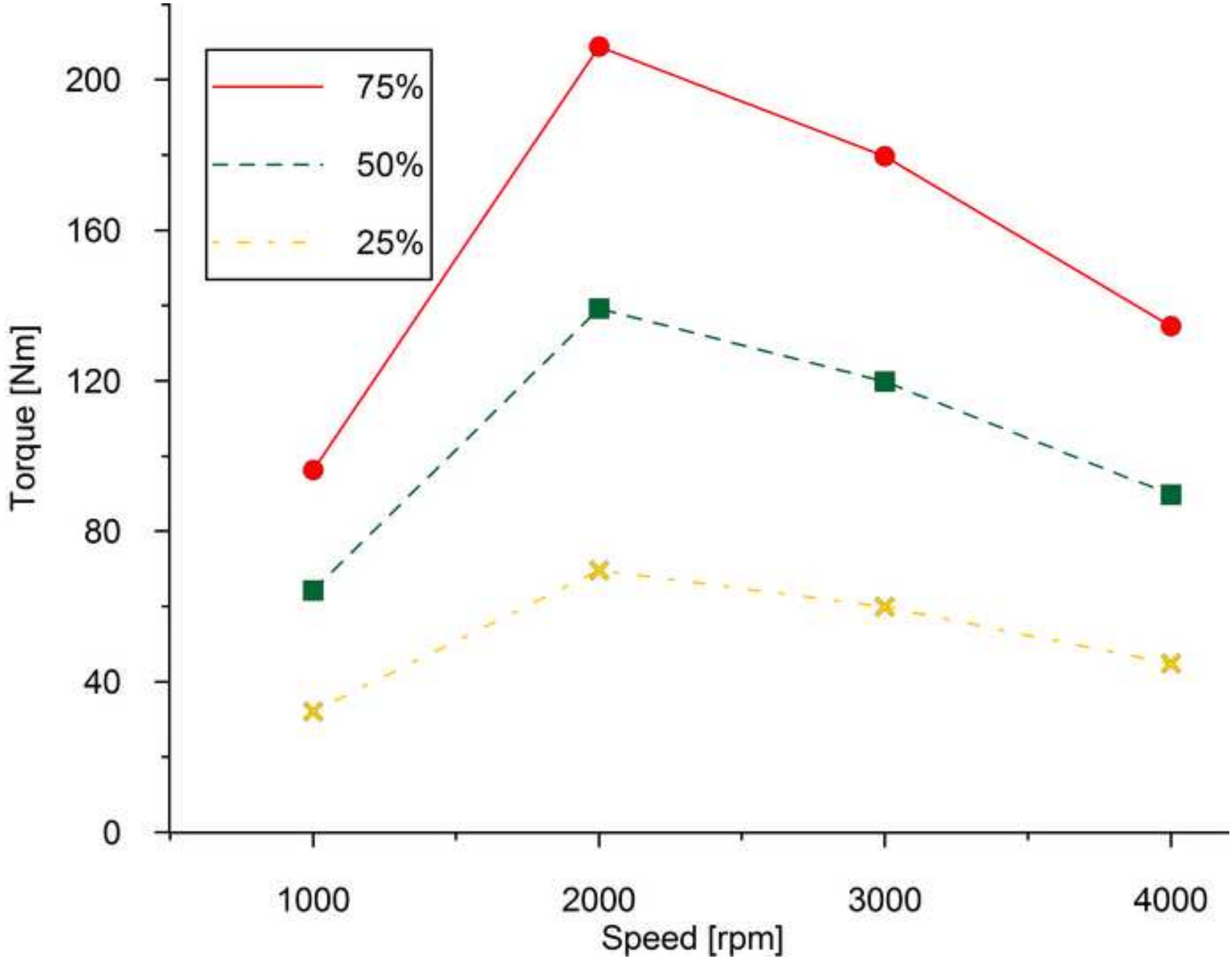
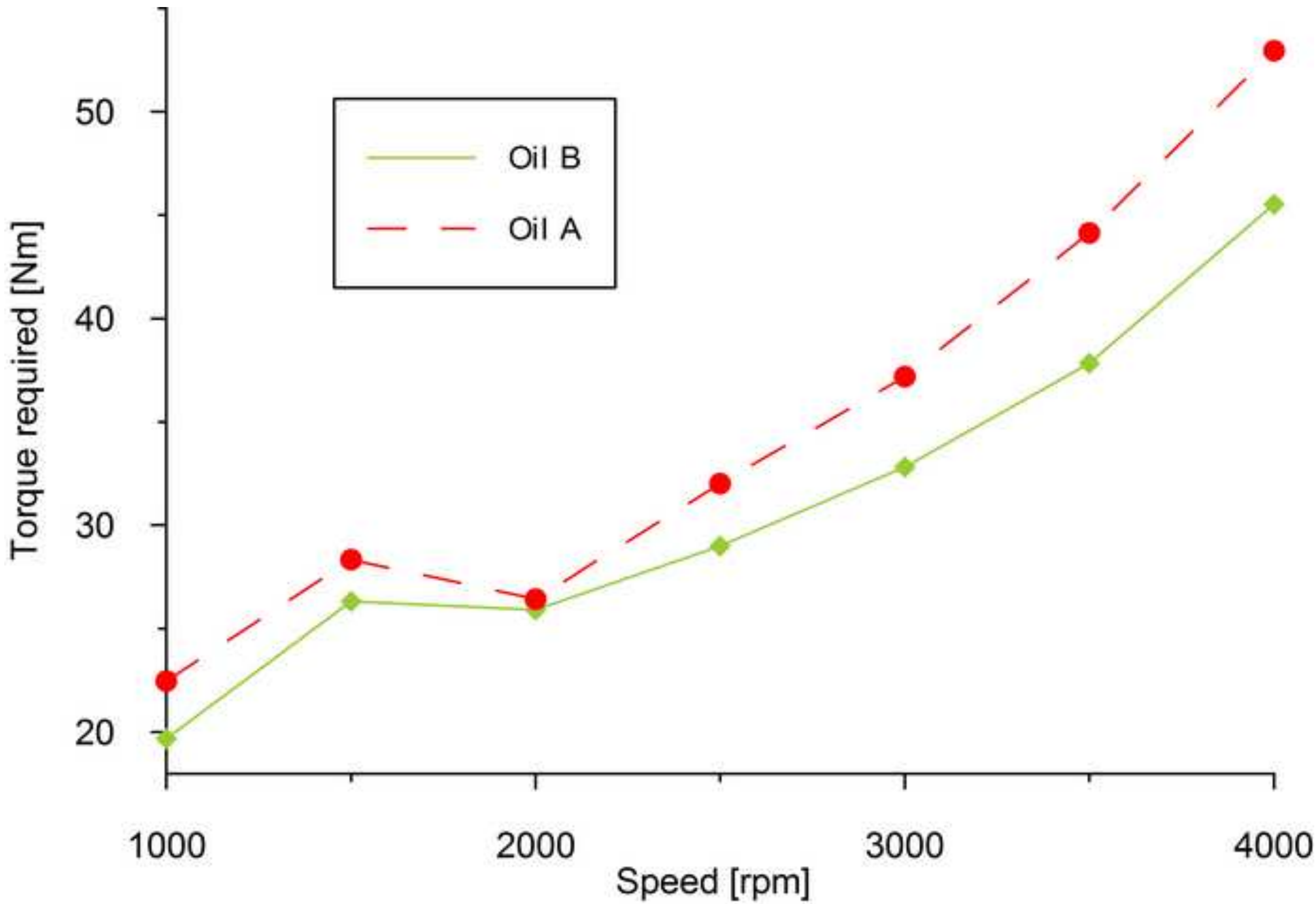
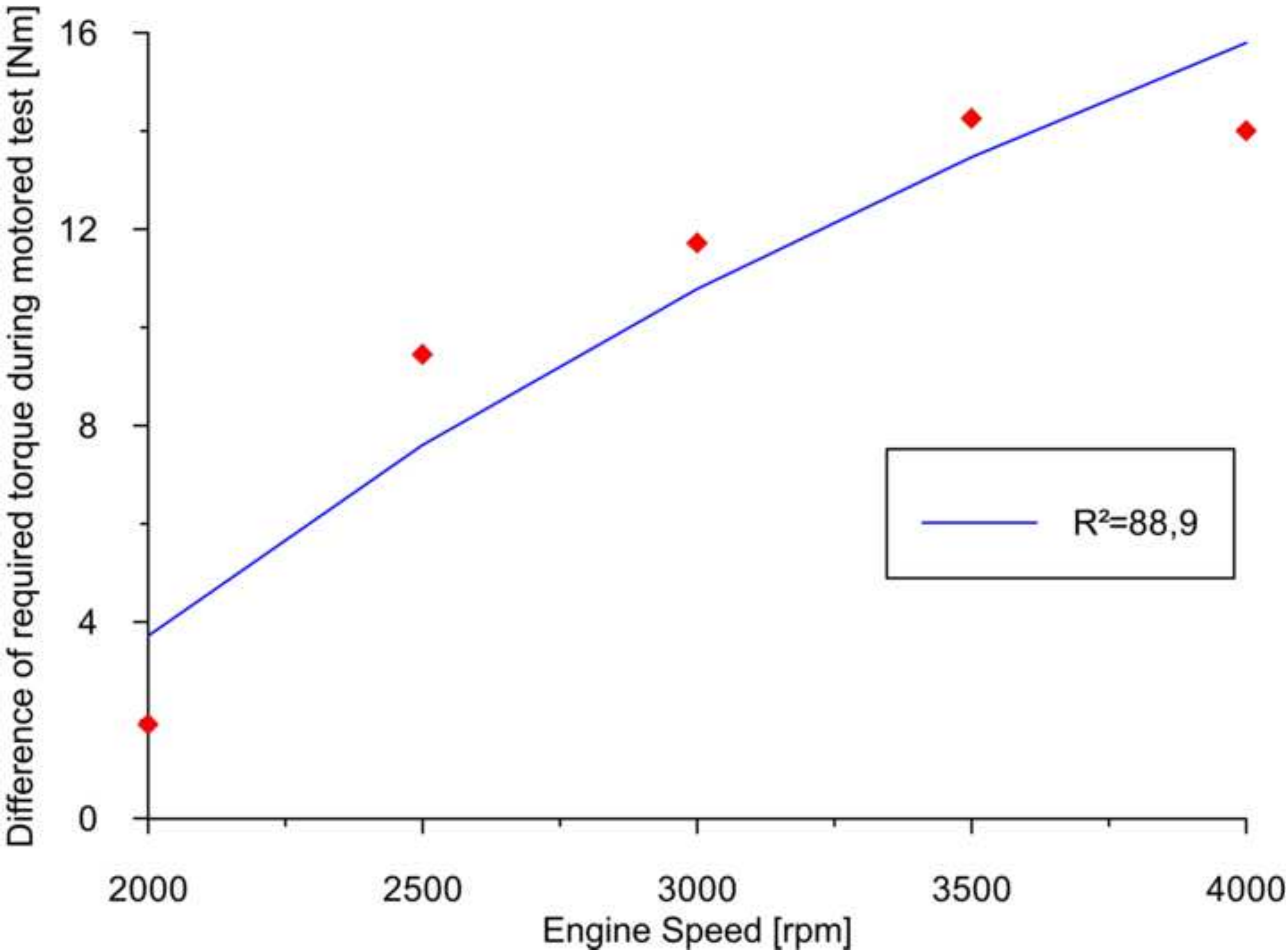

75%
50%
25%
200
160
120
80
40
0
Torque [Nm]
1000
2000
3000
4000
Speed [rpm]

FIG2 Color



Oil B
Oil A
50
40
30
20
Torque required [Nm]
1000
2000
3000
4000
Speed [rpm]

FIG3 Color



16
12
8
4
0
Difference of required torque during motored test [Nm]
2000
2500
3000
3500
4000
Engine Speed [rpm]
R²=88,9

FIG4 Color

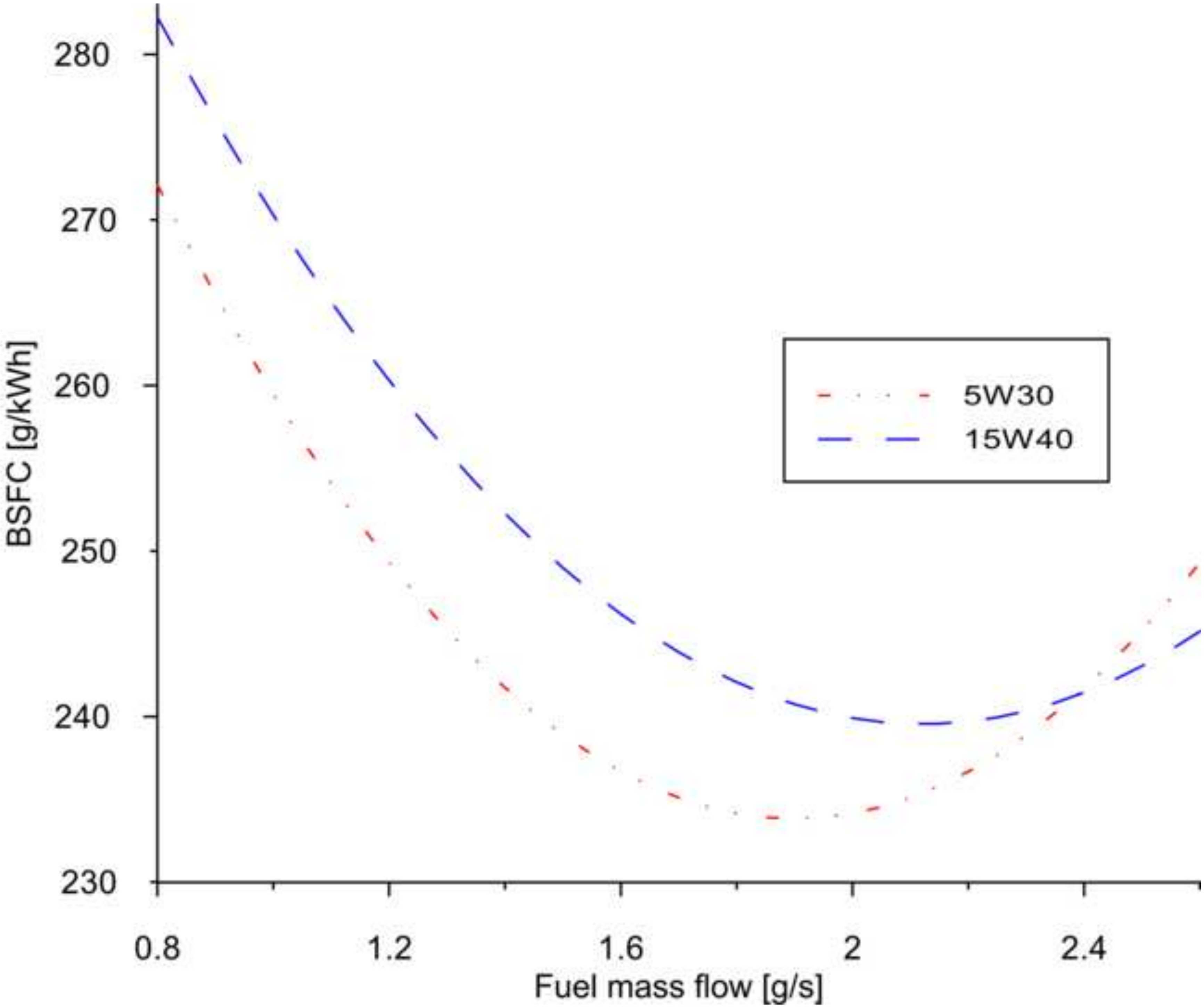
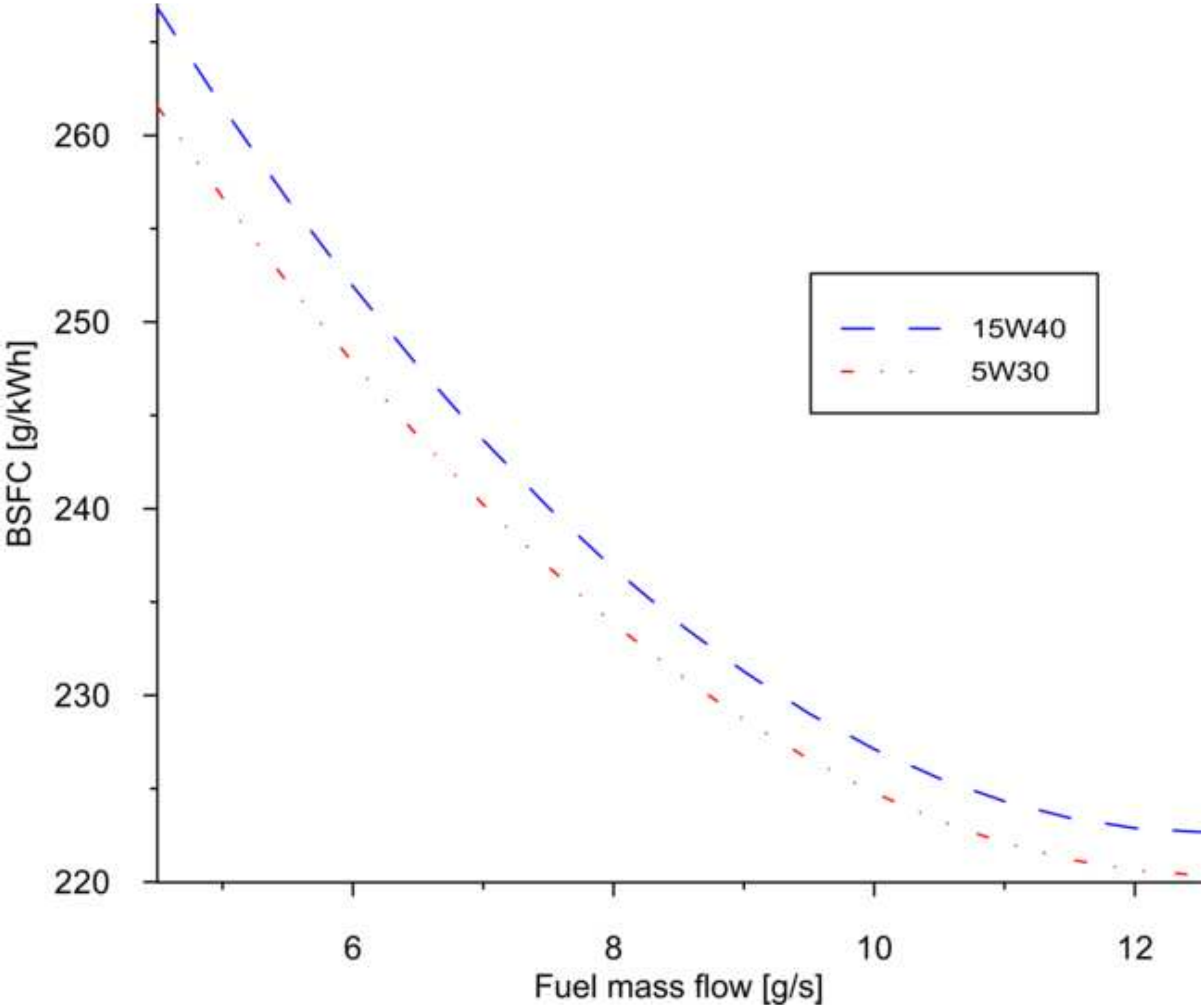

280
270
260
250
240
230
BSFC [g/kWh]
0.8
1.2
1.6
2
2.4
Fuel mass flow [g/s]
5W30
15W40

FIG5 Color



15W40
5W30
260
250
240
230
220
BSFC [g/kWh]
6
8
10
12
Fuel mass flow [g/s]

FIG6 Color

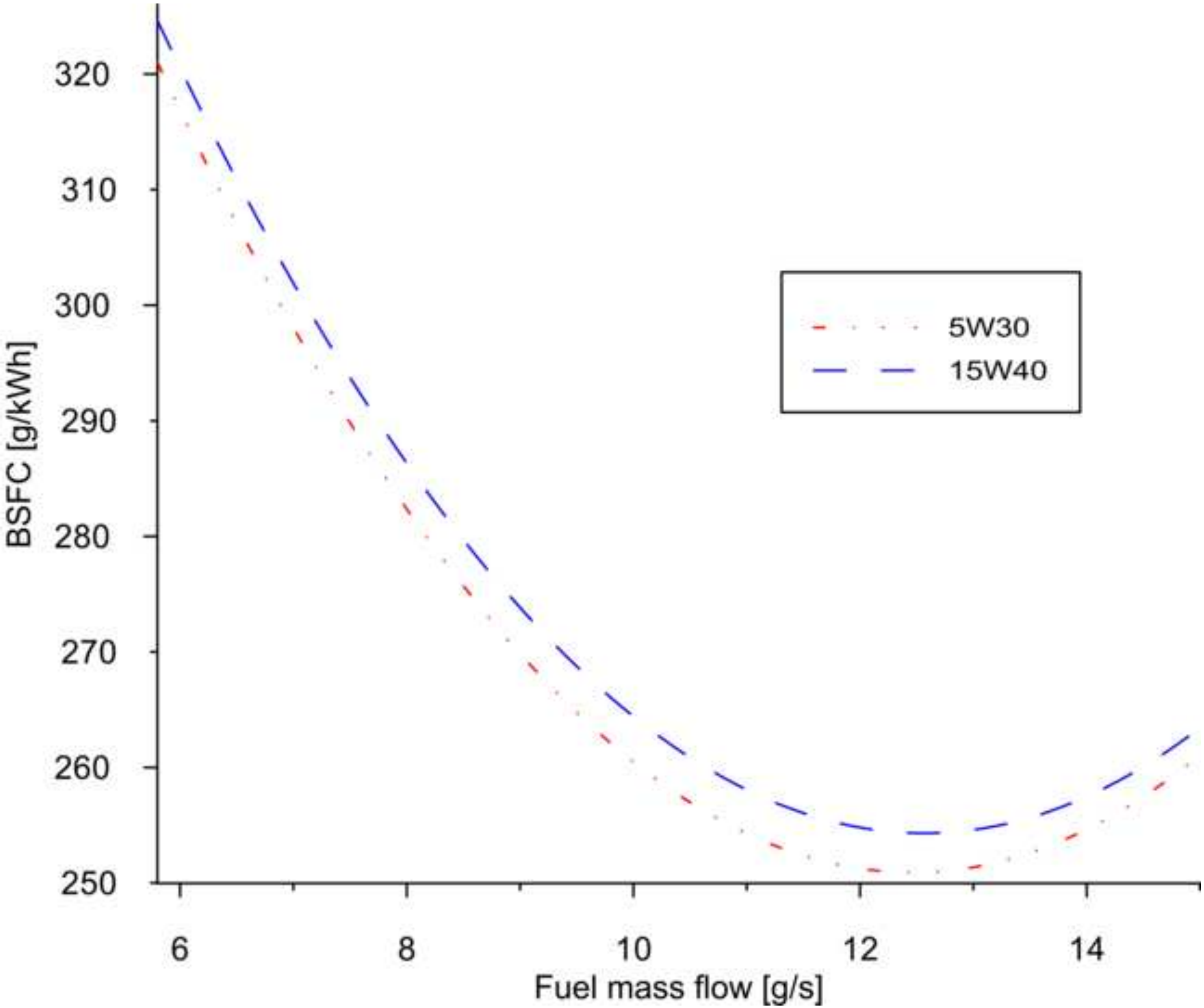

320
310
300
290
280
270
260
250
BSFC [g/kWh]
6
8
10
12
14
Fuel mass flow [g/s]
5W30
15W40

FIG7 Color

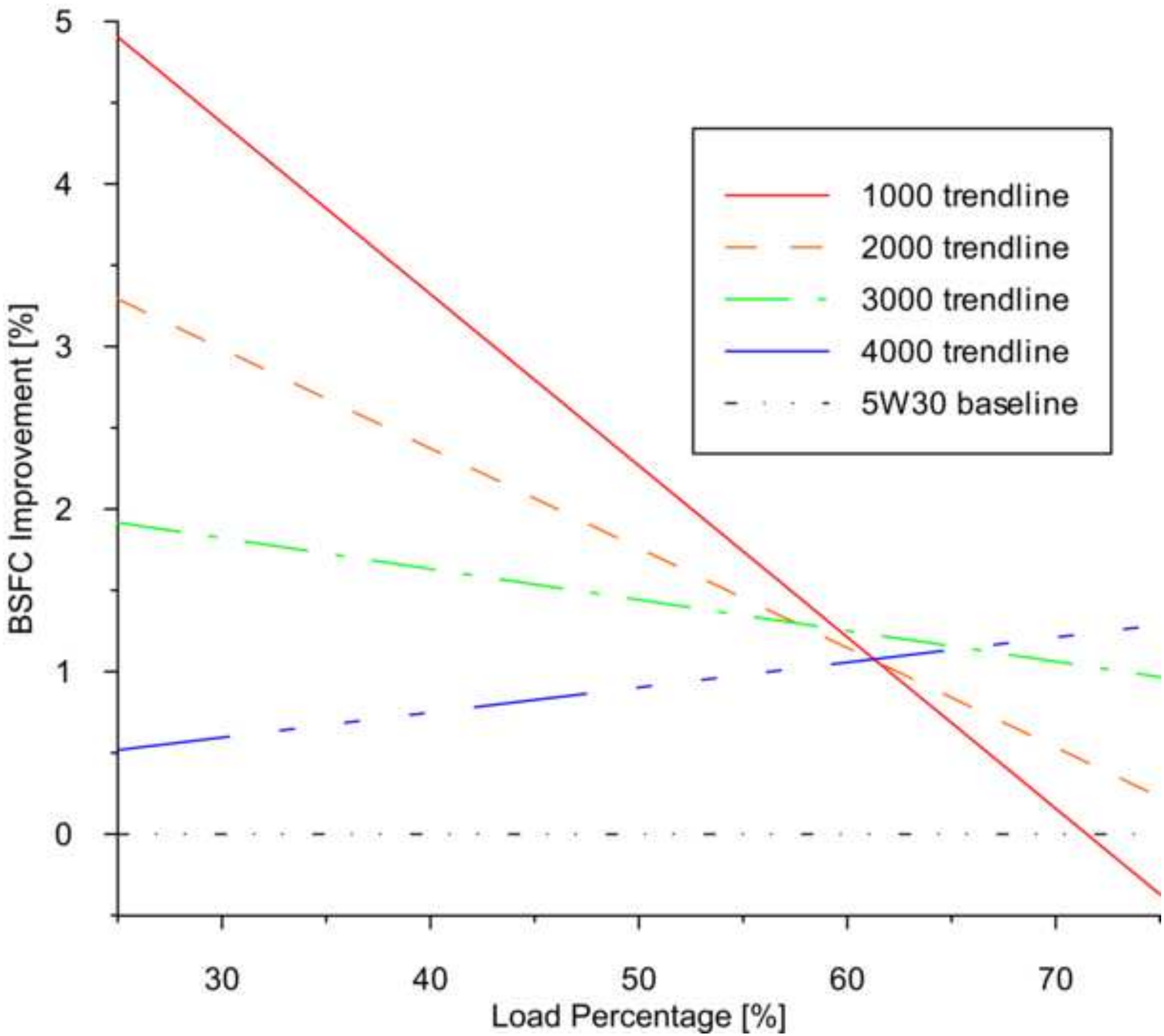
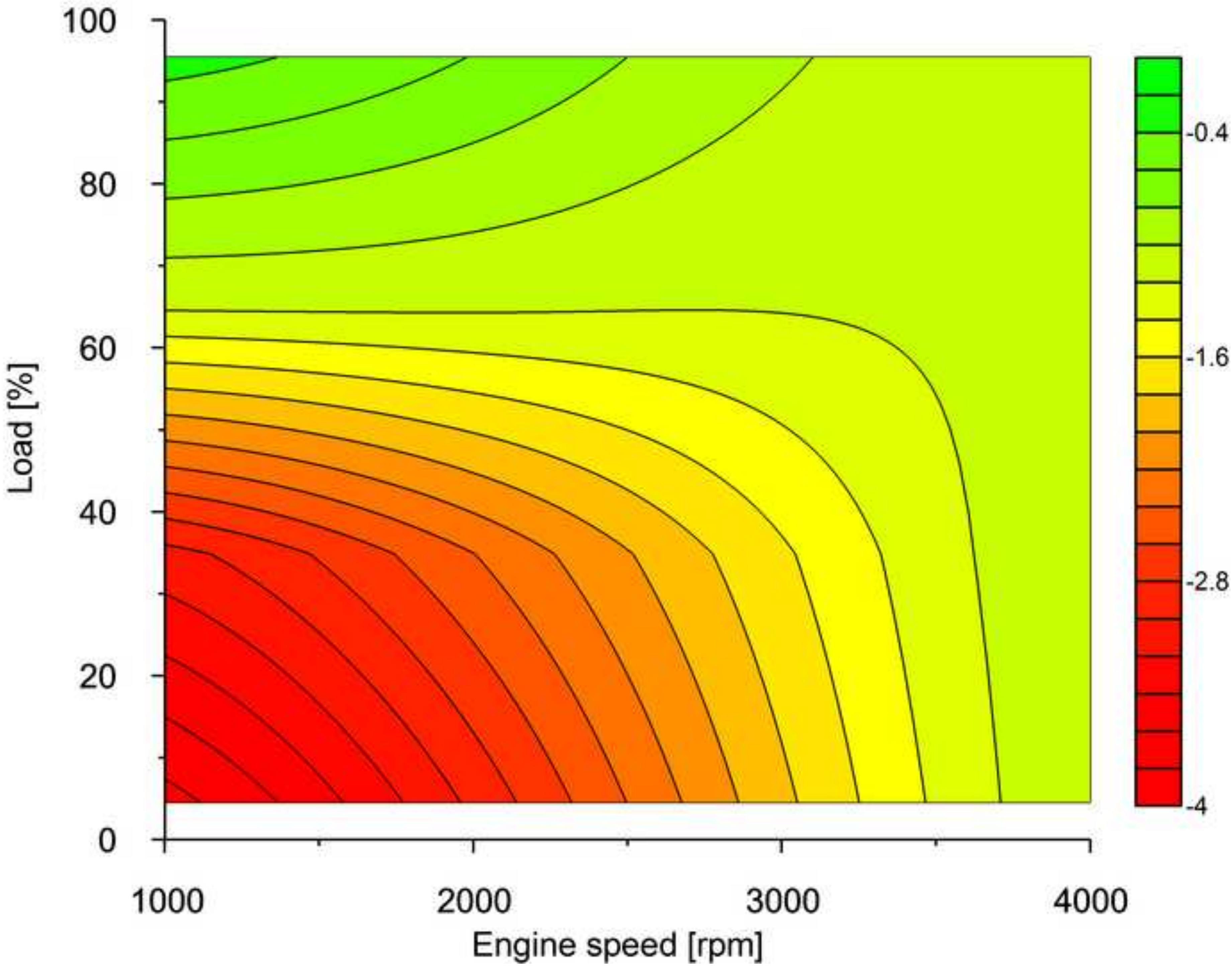

5
4
3
2
1
0
BSFC Improvement [%]
30
40
50
60
70
Load Percentage [%]
1000 trendline
2000 trendline
3000 trendline
4000 trendline
5W30 baseline

FIG8 Color



100
80
60
40
20
0
Load [%]
1000
2000
3000
4000
Engine speed [rpm]
-0.4
-1.6
-2.8
-4

FIG9 Color

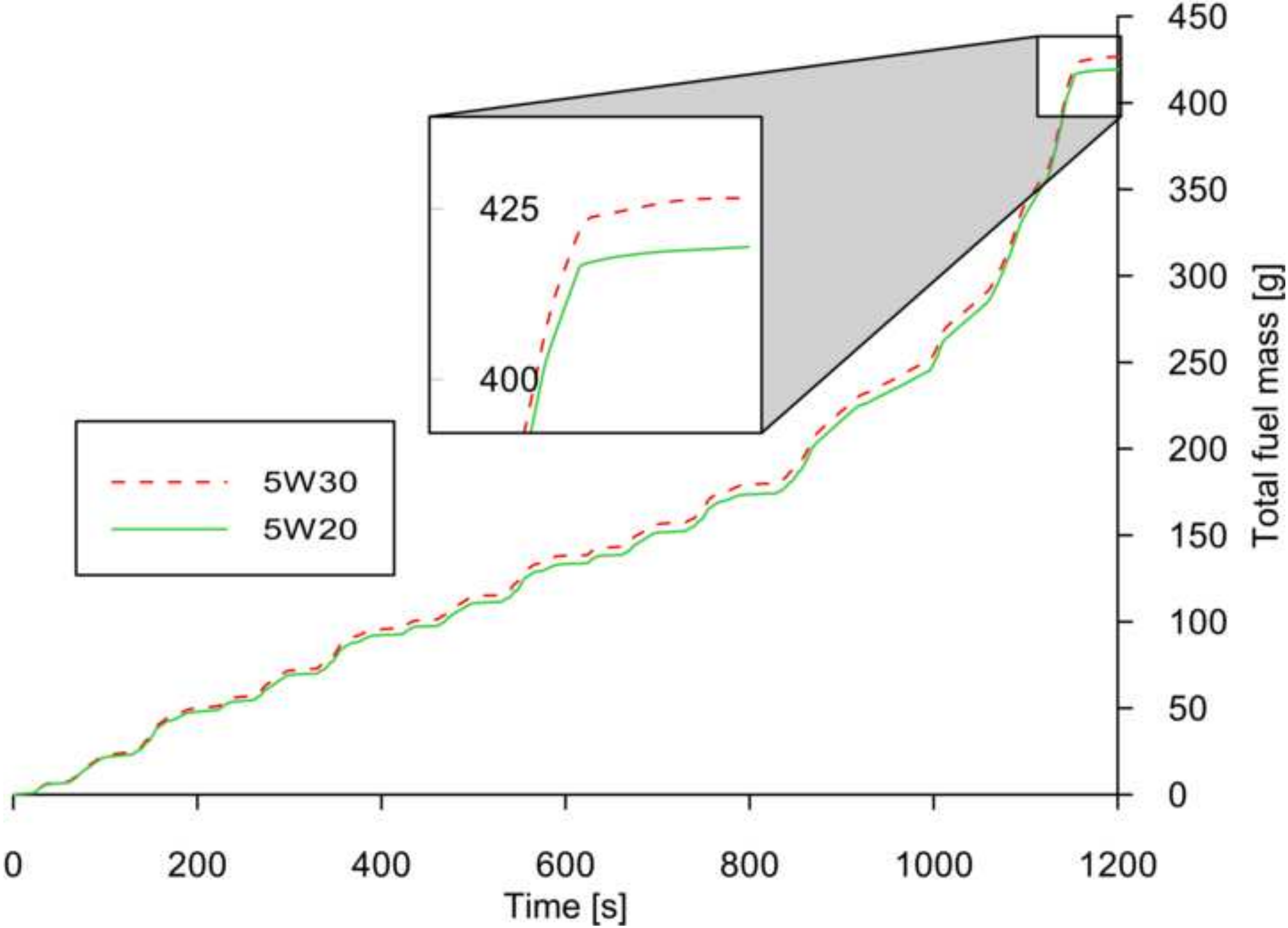

425
400
5W30
5W20
0
200
400
600
800
1000
1200
Time [s]
450
400
350
300
250
200
150
100
50
0
Total fuel mass [g]

FIG10 Color

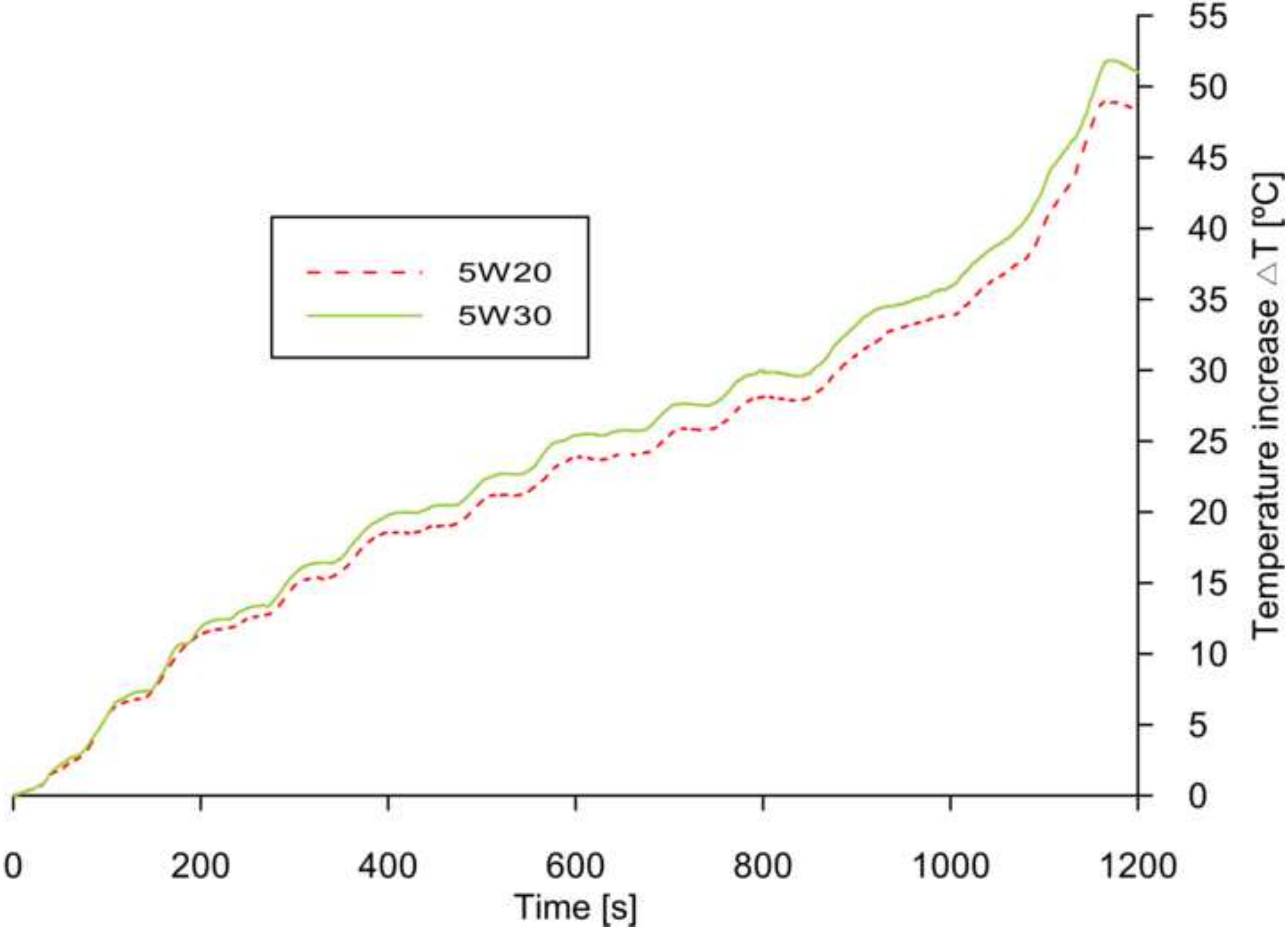

5W20
5W30
0
200
400
600
800
1000
1200
Time [s]
0
5
10
15
20
25
30
35
40
45
50
55
Temperature increase △T [ºC]

FIG11 Color

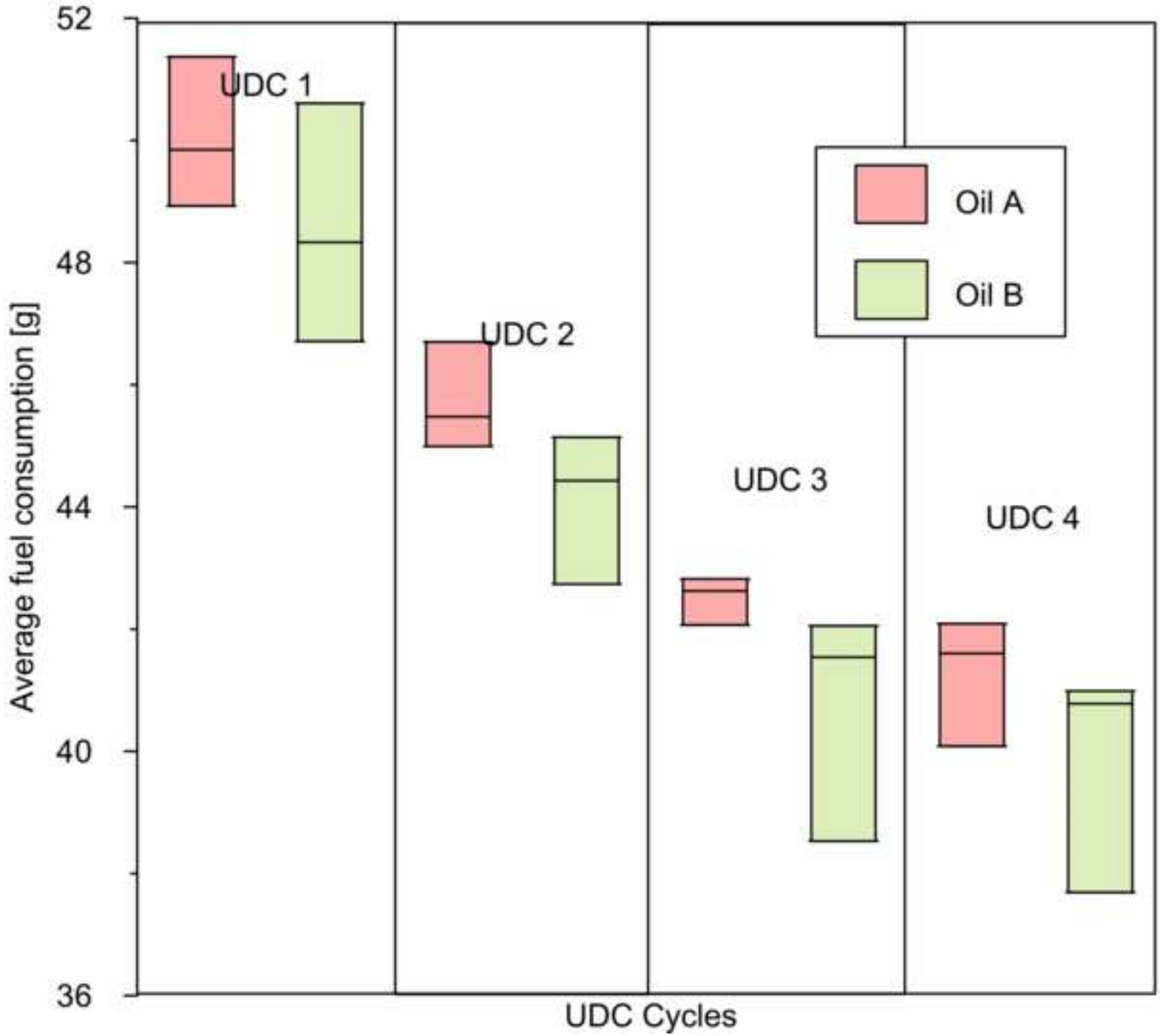

52
48
44
40
36
Average fuel consumption [g]
UDC 1
UDC 2
UDC 3
UDC 4
Oil A
Oil B
UDC Cycles

FIG12 Color

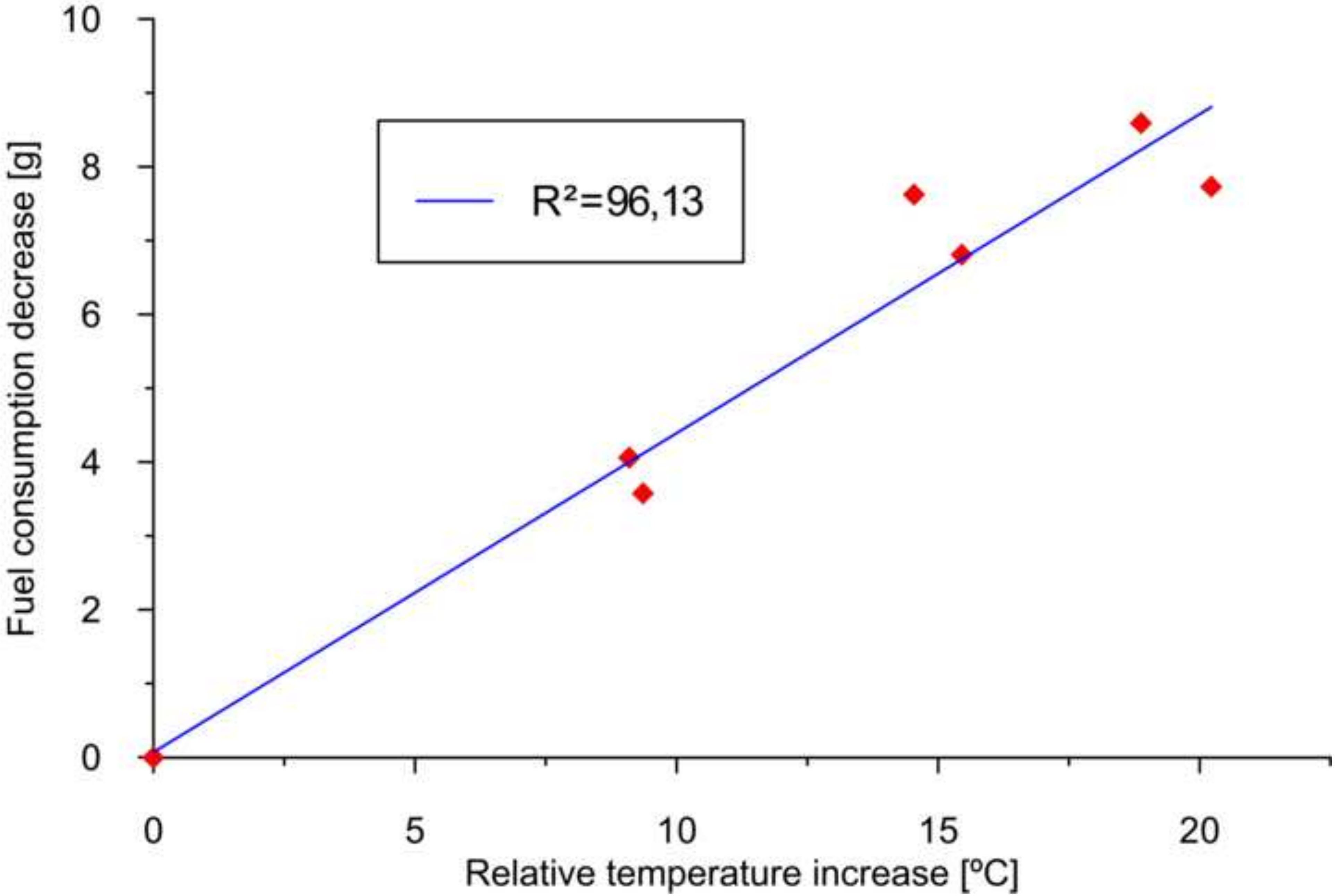

10
8
6
4
2
0
Fuel consumption decrease [g]
R²=96,13
0
5
10
15
20
Relative temperature increase [ºC]

FIG13 Color

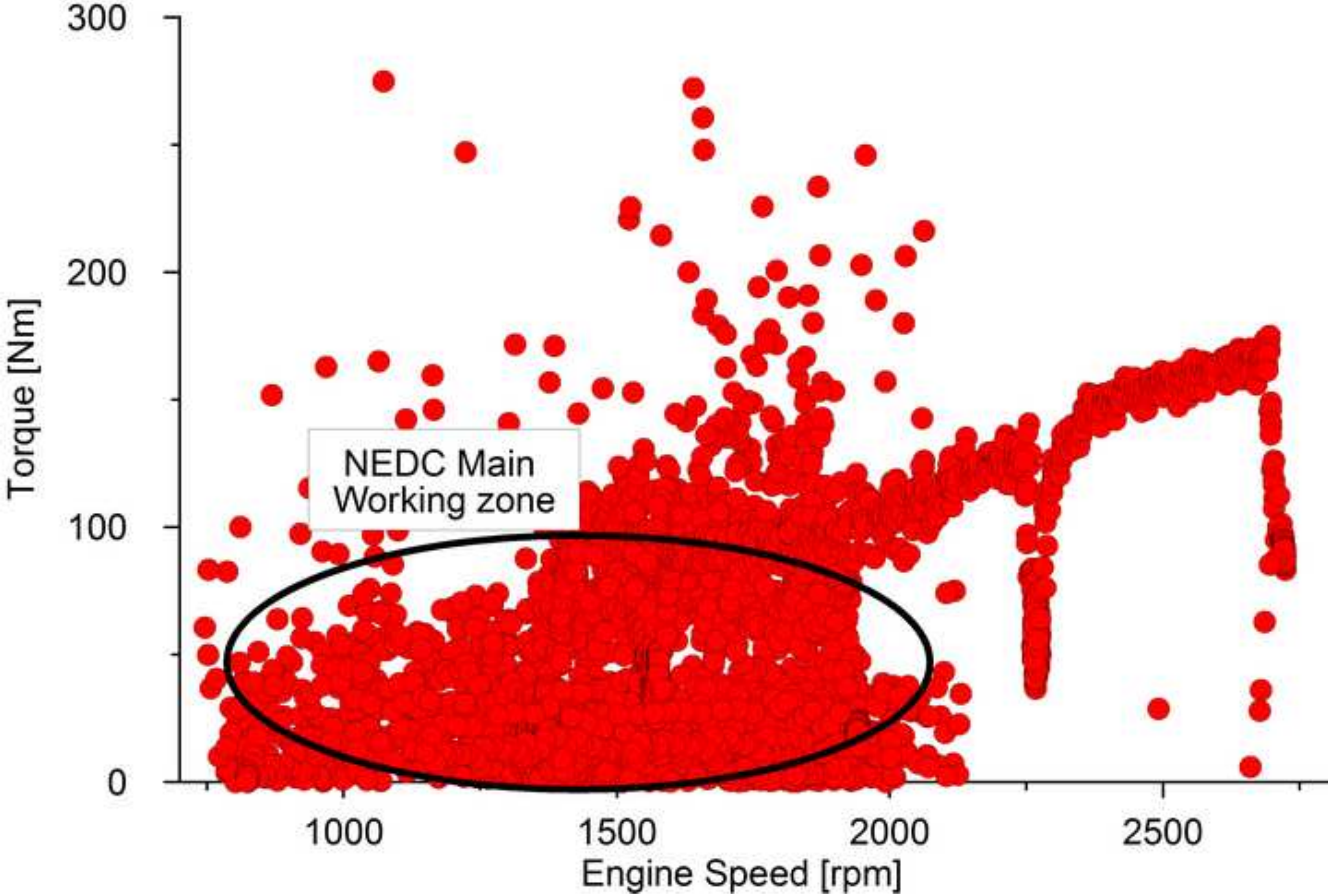
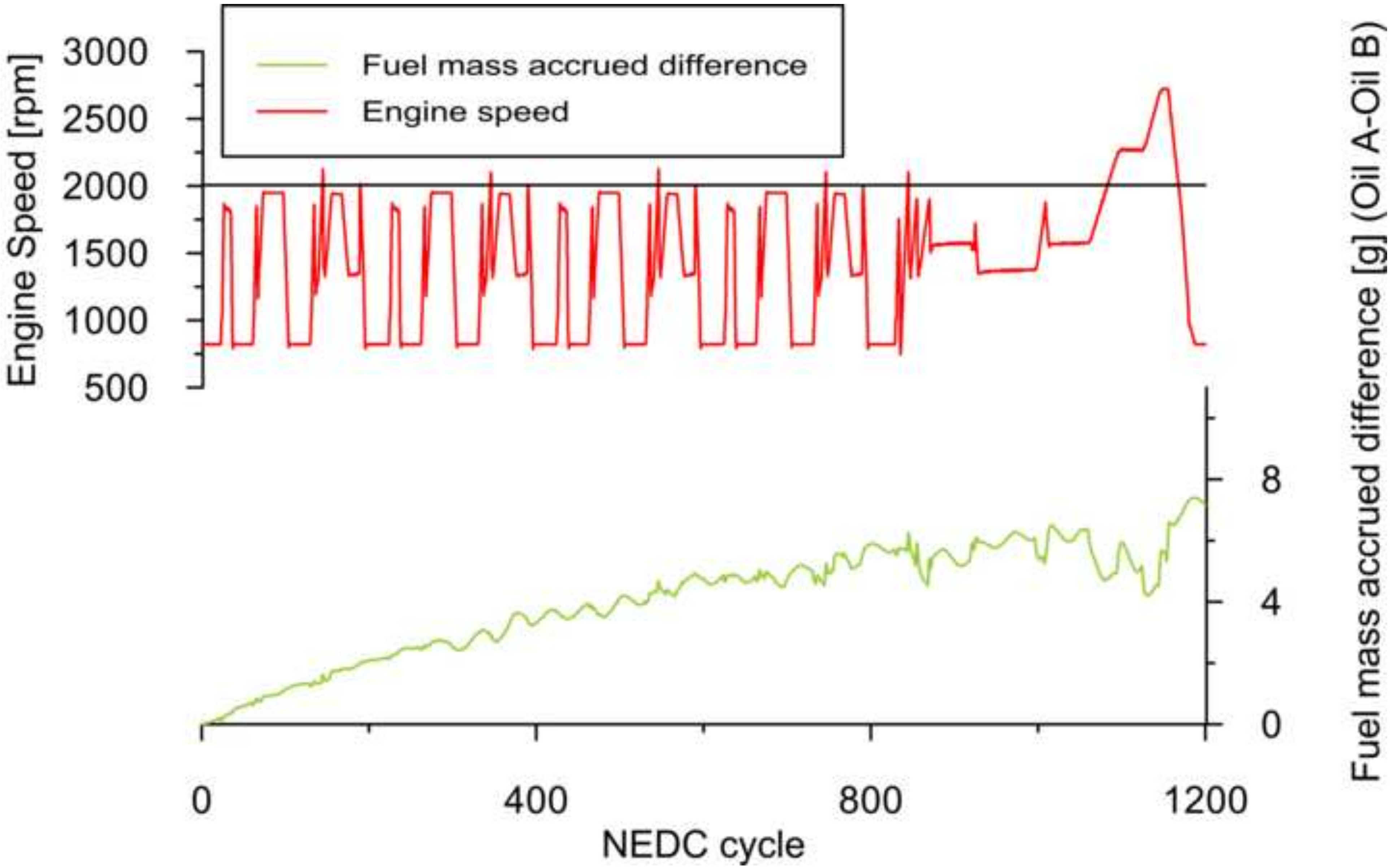

300
200
100
0
Torque [Nm]
1000
1500
2000
2500
Engine Speed [rpm]
NEDC Main
Working zone

FIG14 Color


Fuel mass accrued difference
Engine speed
Engine Speed [rpm]
3000
2500
2000
1500
1000
500
Fuel mass accrued difference [g] (Oil A-Oil B)
8
4
0
0
400
800
1200
NEDC cycle