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Potential of Low Viscosity Oils to Reduce CO_2 Emissions and Fuel Consumption of Urban Buses Fleets.

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Abstract

This paper shows the results of a comparative fleet test which main objective was to measure the influence of Low Viscosity Oils (LVO) over the fuel consumption and CO_2 emissions of urban buses. To perform this test, 39 urban buses, classified into candidate and reference groups depending on the engine oil viscosity, covered a 60000 km mileage corresponding to two standard Oil Drain Interval (ODI). In the same way, for 9 buses of the 39 buses, the effect of differential LVO over fuel consumption and their interaction with engine LVO was assessed during the second ODI.

Test results confirm that the use of LVO could reduce fuel consumption, hence CO_2 emissions. However, special attention should be taken prior its implementation in a fleet, particularly if the vehicles are powered by engines with high mechanical and thermal stresses during vehicle operation because this could lead to friction losses increase, loss of the potential fuel

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consumption reduction of LVO and, in the worst scenario, higher rates of engine wear.

Keywords:
Low Viscosity Oils, CO_2 reduction, Fleet test, Urban Buses, Fuel consumption, Engine efficiency

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Highlights

- A comparative test between two groups of urban buses focused on define the effect of Low Viscosity Oils (LVO) on the buses fuel consumption.
- 39 buses involved, of 3 different models (2 Diesel models and 1 CNG model). Each bus reached an average mileage of 60000 km corresponding to two rounds of its Oil Drain Interval (ODI).
- During a complete ODI, the CO_2 emissions could be reduced by 1 Ton or 2 Ton per bus depending on the engine technology and fuel used.
- Fuel consumption reduction could reach values between 1% and 4% depending on the engines oil SAE grade differences, bus model and fuel used.
- The effect of (LVO) strongly depends on the engine constructive characteristics and even more on its operating parameters as mean effective pressure.

1. Introduction

Nowadays research and development departments of road transportation OEM's are focused on CO_2 emissions reduction, following the global trend of industry to tackle the Global Warming. This concern has been traduced in CO_2 emissions standards in a vast number of industrialized countries. Although these regulations have been set for light duty passenger cars initially, the oncoming trend is to embrace Heavy Duty Vehicles (HDV) as well. It has to be mentioned that research in the HDV segment during the last years has been dedicated to reduce pollutant emissions, especially CO, NO_x and particulate matter; this trend is evident when the progression limits of the Euro emission standards is analyzed[1]. For the above stated reasons, to reduce CO_2 emissions has become an important matter for the road transportation segment and, even when the number of HDV is small compared to the number of passenger vehicles, their share in the total amount of CO_2 emissions is remarkable. Getting deeper on this topic, Holmberg et al.[2] have plotted that from the total energy used in transportation, nearly 73% corresponds to the road segment and of it 36% corresponds to HDV, making this segment a key target where an improvement in efficiency could lead to appreciable energy savings. Among many others, one interesting and specific type of HDV is the urban bus, which energy shares are about 4% of the transportation sector. Some interesting characteristics of this type of vehicles are pointed out by Holmberg as well; they rely on diesel fuel due the extended use of ICE, they have a repetitive duty cycle which leads to homogeneous energy consumption, and they are usually part of fleets which makes easier to influence decision-making in order to implement methods or policies to enhance their energy efficiency. Regarding the buses duty cycle, previous works like Schubert et al.[3] and Tormos et al.[4] have characterized it into a low mean speed profile which can be simplified into the trapezium cycle with four different stages as it can be seen in Figure 1. The first stage comprises the idle operation, which means that it has stopped but the engine is still running. During the second stage Tormos et al. have assumed that the bus driver fully pushes the gas pedal and the engine is driven nearly full loaded since this type of vehicles usually have automatic gear-boxes. During the third stage the vehicle reaches the top cycle speed which tends to remain steady and the engine is working at low loads. Last stage corresponds to retardation where the vehicle drives the engine and the injection system does not inject fuel until the bus stops again. During the four stages the energy that comes from the fuel combustion in the ICE is used for different purposes; during idle energy is used mainly to overcome ICE inner friction losses, during acceleration the energy is used to break the bus inertia in order to reach the top speed, and finally, during constant speed the energy is used again mainly to overcome losses and the effect of drag and rolling.

From the cycle energy break down is evident that most of the energy that comes from the fuel is used to overcome the different losses in the vehicle. Several energy distributions for HDV have been proposed by different authors being the type of vehicle and its duty cycle the main factors defining those distributions. Holmberg et al, have proposed the energy break down showed in Figure 2 for urban buses.

An obvious approach to reduce the CO_2 emissions is to tackle the different sources of vehicle losses. This can be done in very different ways: reducing air drag with more aerodynamic vehicle shapes, controlling tires pressure, using Kinetic Energy Recovery Systems (KERS), applying hybridization or reducing engine friction losses. Taking into account that reduction targets expected from the oncoming regulations are high, it seems unlikely to find just one single solution for a full complying of the normative reductions; it is more probable that the integration of several solutions could lead to accomplish the proposed goals. One proven cost-effective way to increase engine efficiency is the use of Low Viscosity Oils (LVO) in order to reduce the friction losses in engine tribo-contacts which represent nearly 10% of the total losses making them a good target in order to enhance engine efficiency, hence reducing CO_2 emissions. To understand how the use of LVO could enhance engine efficiency is crucial to understand engine friction and lubrication. In every pair of elements sliding against each other with relative motion exists a force acting against this movement, that force is friction which depending on the lubricated pair characteristics will require more or less work to be overcome. In order to reduce its effects is normal to use a lubricant, which could be solid, liquid or gaseous. The relationship between the lubricated pair and the friction coefficient is describe by the Stribeck curve (Figure 3)[5]; the curve shows the friction coefficient behavior for all the lubrication conditions, depending mainly on the lubricant rheology (specifically on lubricant viscosity), the relative speed between the moving parts (U) and the normal force held by the parts (F). From the Stribeck curve three main lubrication regimes can be distinguished : the first one, where there is no lubricant layer between the parts in relative motion, allowing direct parts contact which is called Boundary Lubrication Regime, the second one where the lubricant film layer is fully developed and the main resistance is given by the lubricant inner friction known as the Hydrodynamic Lubrication Regime, and a mixture of the previous two with miscellaneous characteristics of boundary and hydrodynamic regimes along the contact interface is called mixed lubrication. Specifically for ICE, several authors[6–8] have studied the friction distribution among the engine lubricated pairs being the most important; the piston-cylinder liner, followed by the bearings and finally the engine distribution system. The engine friction breakdown listed by each author is shown in Table 1.

	Taraza	Comfort	Pulkrabek
Piston Assembly	40%-50%	45%-50%	50%-70%
Bearings	20%-30%	20%-30%	10%-25%
Distribution	7%-15%	7%-15%	25%

Table 1. Different friction distributions among the main engine lubricating pairs, by author.

However, to avoid this generalization Holmberg et al. have proposed a distribution of lubrication regimes for these three lubricated pairs, this time focused on the urban buses, the type of vehicle which is interesting for this study (Table 2). As it can be seen, nearly a 5% of total vehicle losses are present at hydrodynamic lubrication regime.

Bus engine friction losses (10%)	
Piston Assembly	5.5 %
HL	2.2 %
EHDS	2.1 %
ML	0.6 %
BL	0.6 %
Bearings	3 %
HL	3 %
Valve Train	1.5 %
ML	1.5 %

Table 2. Distribution of the friction losses in the main lubrication regimes by lubrication pairs for a bus (year 2000, bus @ 20 km/h).

This specific lubrication regime is important since it is the only one where friction coefficient depends mostly on lubricants viscosity (there is no contact between moving parts, hence the only resistance to movement is the lubricant inner friction driven mainly by lubricant viscosity). This fact opens the possibility to reduce friction coefficient only by reducing oil viscosity. This effect has been measured by several authors in terms of fuel consumption reduction particularly for the passenger cars segment[9–15], however this focus has been changing and some studies have addressed the effect of LVO on HDV efficiency improvement[7, 16–20]. In one of this studies van Dam et al, have studied the influence of the use of LVO in a

Volvo 12D diesel engine break specific fuel consumption. The study was performed at 12 different stationary conditions, using different candidate oils and using as reference a SAE 15W30 viscosity grade, varying engine speed and load (to emulate diverse lubrication regimes). The results are shown in Figure 4, where the influence of the SAE viscosity grade has statistically significance. In the same way, van Dam et al, have demonstrated that the rheological parameter that drives the fuel consumption behavior is the High Temperature High Shear Viscosity (HTHS @150°C measured under ASTM D4683, CEC L-36-A-90, ASTM D 4741 or ASTM D 5481). Other parameters like kinematic viscosity @100°C measured under ASTM D-445 also have presented good correlations with the associated oils fuel economy[20]. However, up to date is hard to find studies where the effect of LVO over fuel consumption has been proven in real conditions. Even more, the equivalence to CO_2 emissions reduction has not been made most of the times, losing a valuable information about this efficiency solution. This paper explores the effect of using LVO on the public urban buses fleet of the city of Valencia (Spain), on its fuel consumption and CO_2 emissions reduction. The test was performed on 39 buses, both diesel and CNG, over a 60000 km mileage each, equivalent to two Oil Drain Interval (ODI) of the buses.

2. Experimental setup

As it was mentioned before, few recent data about the effect of LVO on fuel consumption on a fleet test is available, especially for the HDV segment. The present study was focused on the assessment of the LVO effects on fuel consumption over nearly 16 months where each bus reached a mileage around 60000 km. In addition, the effect of differential LVO over fuel consumption and the interaction effect between differential and engine oils were studied, using 9 of the 39 buses during their second ODI. Regarding consumption, it was calculated from the fuel reposition data and the global positional system (GPS) of each bus being both values taken on a daily basis. The design of the test, buses models and characteristics, and used oils will be discussed in this section.

2.1. Test buses

39 urban buses of EMT-Valencia public transport fleet were tested. This buses belonged to three specific bus models which main characteristics are described in Table 3.

Characteristic	Diesel I	Diesel II	CNG
Year	2008	2010	2007
Length / width / height [m]	17.94/2.55/3	11.95/2.55/3	12/2.5/3.3
Engine displacement [cm^3]	11967	7200	11967
Cylinders	6	6	6
Max. effect power [kW]	220 @ 2200 [1/min]	210 @ 2100 [1/min]	180 @ 2200 [1/min]
Max. effect torque [Nm]	1600 @ 1100 [1/min]	1100 @ 1100 [1/min]	880 @ 1000 [1/min]
Crankcase volume [l]	31	29	33
BMEP [bar]	16.8 @ 1100 [1/min]	19.55 @ 1100 [1/min]	9.24 @1000 [1/min]
Thermal load [W/mm^2]	2,85	3,97	2,33
Turbo-charging	Turbo + Intercooler	Turbo + Intercooler	Turbo + Intercooler
EGR [-]	NO	NO	-
Valve train config.	OHV Roller Follower	OHV Cam Follower	OHV Cam Follower

Table 3. Buses main characteristics

2.2. Test Oils

As the core topic of this study was the evaluation of engine oil viscosity effect on HDV fuel consumption, the selection of the oils to test was crucial even more when the vehicles in test were still being used within the fleet operation while the test was performed. van Dam et al. studies has proven that kinematic viscosity at 100°C and HTHS viscosities are the oil parameters which affect the most the related fuel consumption being that a key factor for the oil selection. It as to be said that commercial oils were used to this test all of them approved by the buses OEMs.

To evaluate the effect of engine LVO over the buses fuel consumption, four different oils were used. It has to be mentioned that, for each model only two oils were used, one as a candidate and one as reference.

Regarding the effect of differential LVO over buses fuel consumption, two different oils were used, and only one Diesel I model was involved, during the second ODI, or 30000 km.

The main characteristics of engine and differential oils used can be seen in Table 4.

Oil Used as	15W40 Ref	10W40 Low SAPS Ref	5W30 Cand	5W30 Low SAPS Cand	80W90 Ref	75W90 Cand
Used in	Diesel I	Diesel II/CNG	Diesel I/II	CNG	Diesel I	Diesel I
Base	API G-I	API G-III	API G-III+IV	API G-III+IV	[-]	[-]
kV@40°C	108	96	71	68	131	102
kV@100°C	14.5	14.4	11.75	11.7	14.3	15
HTHS @150°C	4.082	3.853	3.594	3.577	[-]	[-]
Viscosity Index	> 141	> 145	> 158	< 169	105	154

Table 4. Test oils properties

2.3. Routes

It is well known that fuel consumption of one vehicle could vary significantly depending on the road and route characteristics: the number of stops, the average speed, and the slope of the road. To avoid these effects, all the buses of each model were scheduled to work on the same route for the 60000 km of the tests. The parameters of the specific routes can be observed in Table 5.

Route	Buses	Lenght [km]	Average speed [km/h]	Bus stops	Type
10	12 CNG	17.5	11.1	66	Urban
70	10 Diesel II	17.3	12.1	59	Urban
62	8 CNG	18.7	15.1	61	Urban-Extraurban
90	9 Diesel I	12.3	13.5	36	Urban

Table 5. Routes characteristics.

2.4. Fuels

Fuels used during the test were Biodiesel 10 (B10 meeting UNE-EN 14214/2003) for Diesel I & II buses and CNG (meeting UNE-EN ISO 15403-1:2008).

3. Calculation

3.1. Fuel consumption

A daily basis calculation of buses fuel consumption was made by means of mileage performed and liters of fuel consumed. Covered distance was measured via GPS, on the other hand fuel consumed was measured by refueling both diesel and CNG buses. The diesel fuel dispenser (Tokheim quantium 110) was able to send the refueling data directly to the Computerized Maintenance Management System (CMMS) in liters. For CNG consumption measurement, a different approach was done. Since the dispenser were not able to provide a single measure per bus, due the CNG refueling facility was erected in such a way that all the CNG fleet had to be connected at the same time for refueling. The fuel is taken directly from the distribution line, then a compressor rise up the pressure to 200 bar, then the buses start the refueling. The fuel flows to buses tanks due the pressure differential until the pressure in the tank reach the 200 bar. As the final pressure and the bus CNG tank volume are known, we used the initial pressure in the tank at the beginning of the refueling to estimate the amount of CNG refueled. All natural gas consumption values listed in this document are referred as Nm3 (normalized cubic meters), that is at 1 atm

(101.325 kPa) pressure and 0°C. Buses fuel tank pressure was read from a mechanical pressure gauge placed by default by the OEM. This device has an accuracy of 0.5% and a thermal deviation of 0.4% of the read pressure by every 10 oset of Celsius degrees from 20°C (calibration temperature).

3.2. LVO effect over fuel consumption calculation

In order to assess the effect of LVO over the fuel consumption of the buses, the complete dataset was subject to Analysis of Variance (ANOVA) technique to quantify the significance of the experimental variables considered. From the facts exposed in the Experimental setup section, it is clear that the experiment could not be completely randomized, (e.g. all oils tested in all bus models or all bus models set to work in all possible routes). Taking into account this situation the ANOVA analysis was performed by bus model, blocking the variability in fuel consumption due differences among buses model and routes. These sort of inconvenience could not be handled due to fleet operation requirements. Variables used to perform the ANOVA analysis were:

- *Daily temperature.* This factor makes reference to the ambient temperature during the test registered in Celcius. This value was introduce as a factor for two reasons: firstly, the inverse relationship between temperature and oil viscosity, and secondly, the use of air conditioning during summer suppose an abnormal power consumption compared with other year seasons. Even though both assumptions are correct, it is clear that the oil temperature during engine operation should tend to be the same once transitional operation has finished, hence, air conditioning will have more specific weight and relation with fuel consumption.

- *Oil mileage.* It is well known that depending on oil formulation and the engine operating parameters, the values of viscosity could change over the ODI. If viscosity tends to be higher at the end of ODI fuel consumption would increase given the extra effort that moving parts must do to overcome lubricants inner friction, if the opposite case happens, that is, viscosity decreases over the ODI, less power, hence less fuel consumption would be required to reach one operation point.
- *Month.* Transportation demand varies across the year (e.g. some places like the beaches often have more visitors during summer than winter, and routes passing near Universities or school would present more demand over class periods). These changes would represent a significant variation in fuel consumption given the load differences.
- *Oil type.* The main factor to be considered during this test. It defines if the oil used in a given bus is candidate (LVO) or reference (baseline).
- *Differential oil type.* In similar fashion as Oil type, Differential oil present two levels depending on oil viscosity. However this factor will only be included in ANOVA for Diesel I buses.
- *Oil type x Differential oil type.* This factor evaluates the interaction between engine and differential oil viscosity regarding vehicle fuel consumption. Due differential oil will be analyzed only for Diesel I

buses, this interaction will only be suitable for this buses model.

4. Results

As buses fuel consumption is the magnitude that can be directly quantified with the proposed methodology, the results are going to be referred in fuel consumption units (l/100 km for Diesel buses and m^3/100 km for CNG buses). Table 6 summarizes the effect of LVO on fuel consumption for each bus model after the vehicles completed a 60000 km mileage. The table also indicates if the resulting fuel consumption benefits are either statistically significant or not, with a confidence level of 95%. In the same way, the limits for confidence interval are included in the table. It has to be noted that for Diesel I buses the effect of LVO on differential over fuel consumption was calculated as well.

	Ref Oil	Cand Oil	Ref-Cand [%]	Ref-Cand [fuel/100 km]	+/- Limits
Diesel I	15W40	5W30	1.83	1.3	0.98
	80W90	75W90	0.58 N.S.	0.4	0.91
Diesel II	10W40 Low SAPS	5W30	0.98 N.S.	0.46	0.53
CNG	10W40 Low SAPS	5W30 Low SAPS	3.7	3.27	0.99

Table 6. Fuel consumption benefits of LVO per bus model. Values with confidence level of 95%. N.S indicates the absence of statistically significant differences.

However, to address the results and particularities for each bus model and their respective test oils, the results are analyzed separately as follows.

4.1. Diesel I buses

Once the test finished, after completing two ODI and performing the ANOVA analysis, it was proven that engine oil viscosity had an effect over Diesel I buses fuel consumption: the buses using SAE 15W40 showed a fuel consumption of 70.9 l/100 km which represents a difference of 1.3% with respect to buses using SAE 5W30 which consumed an average of 69.69 l/100 km as it can be seen on Figure 5. This difference is statistically significant with 95% of confidence level. In the same way the effect of differential oil viscosity was proven through ANOVA(Table 7). As in the case of engine oil, the less viscous oil lead to lower fuel consumption (70.54 l/100 km for SAE 80W90 in contrast to 70.13 l/100 km for SAE 75W90), yet this difference was not statistically significant so even when results seem to be logic it is not possible to completely claim favorable fuel consumption results for LVO.

Factor	SS	DoF	P-Value
Daily Temp [°C]	3662.38	1	0.0
Oil mileage [km]	1895.72	1	0.0004
Engine Oil	1038.29	1	0.0092
Month	4850.19	12	0.0002
Differential Oil	117.48	1	0.3812
Interaction (Engine-Differential)	1620.72	11	0.85

Table 7. ANOVA results for Diesel I buses.

For this type of analysis sometimes it is important to find if there is any level of interaction between certain variables. In this case, it was important to know how engine LVO oils and differential LVO oils interact, it means, if the reduction of fuel consumption presented by engine LVO was maintained, decreased or increased when a differential LVO was used. To figure out how was this interaction and if it has an impact on fuel consumption, it was included in the model, resulting into a positive but not statistically significant interaction between the two levels of the oils as it can be seen in Figure 7, where despite the lack of significance, it is clear that engine LVO combined with differential LVO give the lowest fuel consumption value in comparison with other combinations. As expected the highest fuel consumption occurs if both oils correspond to reference viscosity. The complete values of all combinations can be seen on Table 8.

Engine Oil	Differential Oil	Fuel consumption [l/100 km]
5W30	75W90	62.52
5W30	80W90	69.84
15W40	75W90	70.74
15W40	80W90	71.23

Table 8. Fuel consumption values for the interactions between Engine and Differential oils at two levels.

4.2. Diesel II buses

From ANOVA results (Table 9), fuel consumption difference between the buses using reference SAE 10W40 and the buses using candidate SAE 5W30 was 0.98% as it can be seen on Figure 8. However, these differences could not be proven as statistically significant.

Factor	SS	DoF	P-Value
Daily Temperatue [°C]	3662.38	1	0.0003
Oil mileage [km]	1895.72	1	0.0447
Engine Oil	1038.29	1	0.0814
Month	4850.19	11	0.0000

Table 9. ANOVA results for Diesel II buses.

4.3. CNG buses

After carrying out the 60000 km mileage, the buses that used SAE 5W30 Low SAPS gave a fuel consumption of 85.1 $Nm^3/100$ km, considerably lower than the 88.37 $Nm^3/100$ km of fuel consumption given by the buses using SAE 10W40 Low SAPS. For CNG buses this difference of 3.7% is statistically significant, demonstrating again the benefits of using LVO in terms of fuel consumption. The complete results can be seen on the Table 10 and Figure 9.

Factor	SS	DoF	P-Value
Daily Temp [°C]	670.4	1	0.048
Oil mileage [km]	13561.0	1	0.006
Engine Oil	16733.1	1	0.004
Route	375386.0	1	0.000
Month	4850.19	11	0.0125

Table 10. ANOVA results for CNG buses.

4.4. Additional considerations

As mentioned on section 3.2 some other factors like daily temperature and month were included in the ANOVA analysis. Some of these factors have proven to have significance over the fuel consumption as plotted on table 7, table 9 and table 10. Since the focus of this study is on engine oil viscosity effect over fuel consumption the analysis of the other factors wont be extensive.

Daily temperature: In every case, the daily temperature presented strong significance regarding fuel consumption variation. The highest the temperature the more fuel consumption was reported. From the engine oil point of view this seems to be counter intuitive, however, this is not the case since high temperatures during summer implies the use of air conditioning which consumes engine power to work, hence, fuel consumption increases. As an example, fuel consumption variation due daily temperature can be seen in Figure 10 for Diesel I buses.

Month: Represents the variation in working loads of the buses for a giving month during the year. In this case, the variation in fuel consumption was important for those buses which their route presented higher variations during the year (e. g. seasonality observed in routes heading towards the beach or universities).

Oil mileage: This factor has significant effect over buses fuel consumption. A complementary work related with oil analysis published previously has shown divergence in oils viscosity trends among the bus models [21], however the ANOVA results show a significant decrease in fuel consumption as the oil mileage increases, being lower at the end of the ODI. Since this trend has no correlation with the oil properties under study it is not possible to give any robust condition and a deeper study should be done in the future.

Route: This factor was included for CNG buses only. These buses worked mainly in two routes during test period being the most notable difference the fact that on of them was completely urban and the other had a semi-urban stretch. The differences in fuel consumption between these two routes can be seen on figure 11.

5. Discussion

5.1. CO_2 emissions reduction

The fuel consumption reductions achieved by means of using engine LVO presented in the Results section can be easily translated into CO_2 emissions reductions terms, since the latter is a direct product of fuel combustion in the engine. The absolute differences in fuel consumption among the reference and candidate buses of the three different models are listed in Table 6. Taking into account only the bus models which presented statistically significant differences, the next step consists on finding the equivalence of these benefits in terms of CO_2 emissions for the 60000 km covered by each bus. The normal procedure to calculate the equivalence involves knowing the elementary composition of fuel to calculate the amount of carbon in it, then supposing a stoichiometric combustion, a carbon balance is made in order to calculate the amount of CO_2 produced in the reaction. The complete method and formulas for calculation can be found in the appendix. For Diesel I buses and CNG buses which obtained statistically significant differences, the CO_2 emissions reductions per kilometer were 34.29 g/km and 70.14 g/km respectively. It is worth remembering that each of the test buses covered an average 60000 km mileage during the test hence, the total amount of CO_2 emissions reduction per Diesel I and CNG bus using LVO is easy to plot, being this values 2.05 CO_2 Tons and 4.2 CO_2 Tons respectively.

5.2. Potential of LVO to reduce fuel consumption and CO_2 emissions depending on the engine parameters

From the previous results is easy to note the variation of the fuel consumption benefit of LVO among different bus models. Being engine friction losses the main parameter affected by the use of LVO it would be desirable to establish a correlation of benefits with the type of engine. Looking at engine thermal loads but specially the break mean effective pressure in Table 3 and the fuel consumption differences found in the previous section, one possible approximation would be like the one is plotted on Figure 12.

6. Conclusions

During the field test, SAE 5W30 LVO gave lower fuel consumption than SAE 10W40 and SAE 15W40 for the three bus models used.

For Diesel I buses, SAE 5W30 oil gave 1.3% of fuel consumption benefits compared to SAE 15W40. In the case of differential oils, despite of showing lower fuel consumption, it was not possible to statistically state that SAE 75W90 lead to lower fuel consumption compared to SAE 80W90.

Each Diesel I bus using SAE 5W30 engine oil emitted 2.05 CO2 Tons less than their counterparts using SAE 15W40 engine oil for the 60000 km mileage.

For Diesel II buses, SAE 5W30 oil gave 0.98% of fuel consumption benefits over 10W40 Low SAPS, however this difference was not statistically significant.

For CNG, SAE 5W30 Low SAPS gave 3.27% of fuel consumption benefit over SAE 10W40 Low SAPS.

Each CNG bus using SAE 5W30 Low SAPS engine oil emitted 4.2 CO2 Tons less than their counterparts using SAE 10W40 Low SAPS engine for the 60000 km mileage.

The effectiveness of LVO to reduce fuel consumption relies strongly on the mechanical and thermal loads of the engine.

For fleet tests where repeatability is poor due noisy factors, a high number of test runs is required to obtain fuel consumption differentiation.

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Appendix

CO_2 emissions calculation

CO_2 emissions are a direct product of fuel combustion. As B10 and CNG were the two fuels used in the test, the elementary composition of these fuels would be required to perform the calculation. The following compositions can be supposed:

- Diesel: $C_{12}H_{22}$
- Biodiesel B100: $C_{19}H_{35}O_2$
- CNG: CH_4

The combustion reactions of these fuels are
Diesel:

$$2\,C_{12}H_{22} + 35\,O_2 \longrightarrow 24\,CO_2 + 22\,H_2O \tag{A.1}$$

B100:

$$C_{19}H_{35}O_2 + 26.75\,O_2 \longrightarrow 19\,CO_2 + 17.5\,H_2O \tag{A.2}$$

CNG:

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O \tag{A.3}$$

If carbon molar mass is 12 g/mol, oxygen is 16g/mol and Hydrogen is 1 g/mol, the molar mass for each fuel and combustion product are:

Compound	Molar mass [g/mol]
CO_2	44
CH_4	16
$C_{11}H_{22}$	166
$C_{19}H_{35}O_2$	295

Table A.1. Molar mass of the different compounds involved in fossil fuels combustion.

Hence the CO_2 emissions per g of fuel are:

Fuel	CO_2/fuel [g/g]
Diesel	3.18
B100	2.83
CNG	2.75

Table A.2. Grams of CO_2 emissions per gram of fuel.

Given the fuels densities:

Fuel	Density
Diesel	835 g/l
B100	880 g/l
CNG	1098 kg/Nm^3

Table A.3. Density values for different fuels.

With the given values the equivalent CO_2 emissions for a given fuel consumption could be calculated by:

$$\text{CO}_2 \text{ emissions } [\frac{g}{km}]\text{= fuel consumption } [\frac{l}{100km}] \text{ x fuel density } [\frac{g}{l}] \text{ x CO}_2 \text{ equivalence x } \frac{1}{100} \tag{A.4}$$

Figure captions

- Figure 1. Urban bus duty cycle. Adapted from Schuber et al[3].
- Figure 2. Energy distribution for urban buses[2].
- Figure 3. Stribeck curve. Adapted from Payri et al[5].
- Figure 4. SFC Improvement for different SAE viscosity grade oils[18].
- Figure 5. Average fuel consumption for reference and candidate buses of Diesel I model.
- Figure 6. Average fuel consumption for reference and candidate buses of Diesel I model.
- Figure 7. Interaction effects between engine and differential oils for Diesel I buses.
- Figure 8. Average fuel consumption for reference and candidate buses of Diesel II model.
- Figure 9. Average fuel consumption for reference and candidate buses of CNG model.
- Figure 10. Daily temperature and oil mileage effects over fuel consumption of Diesel I buses.
- Figure 11. Route effect over fuel consumption for CNG buses.
- Figure 12. Fuel consumption benefits of LVO vs. engine break mean effective pressure (BMEP).

Figure1_color

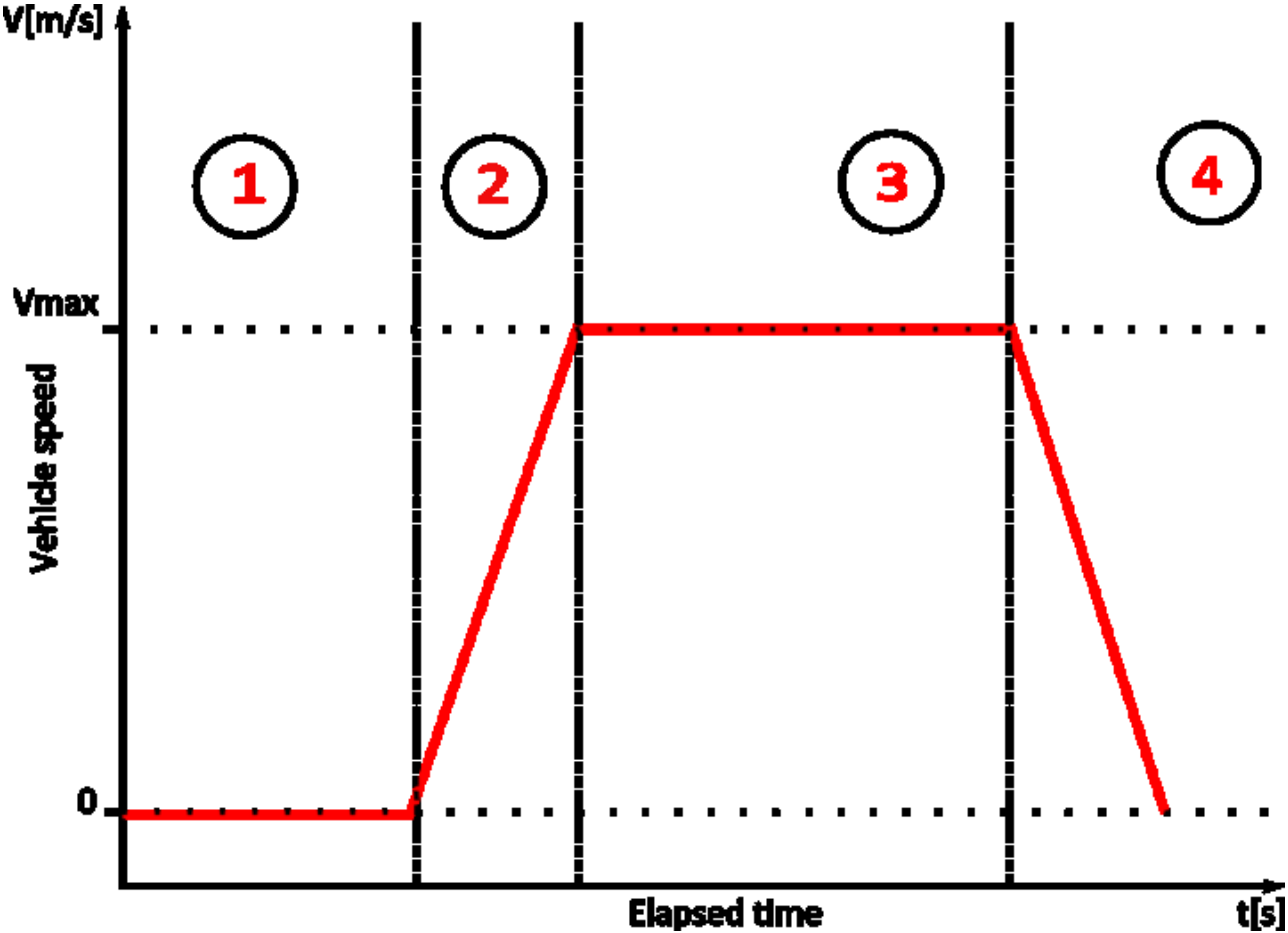
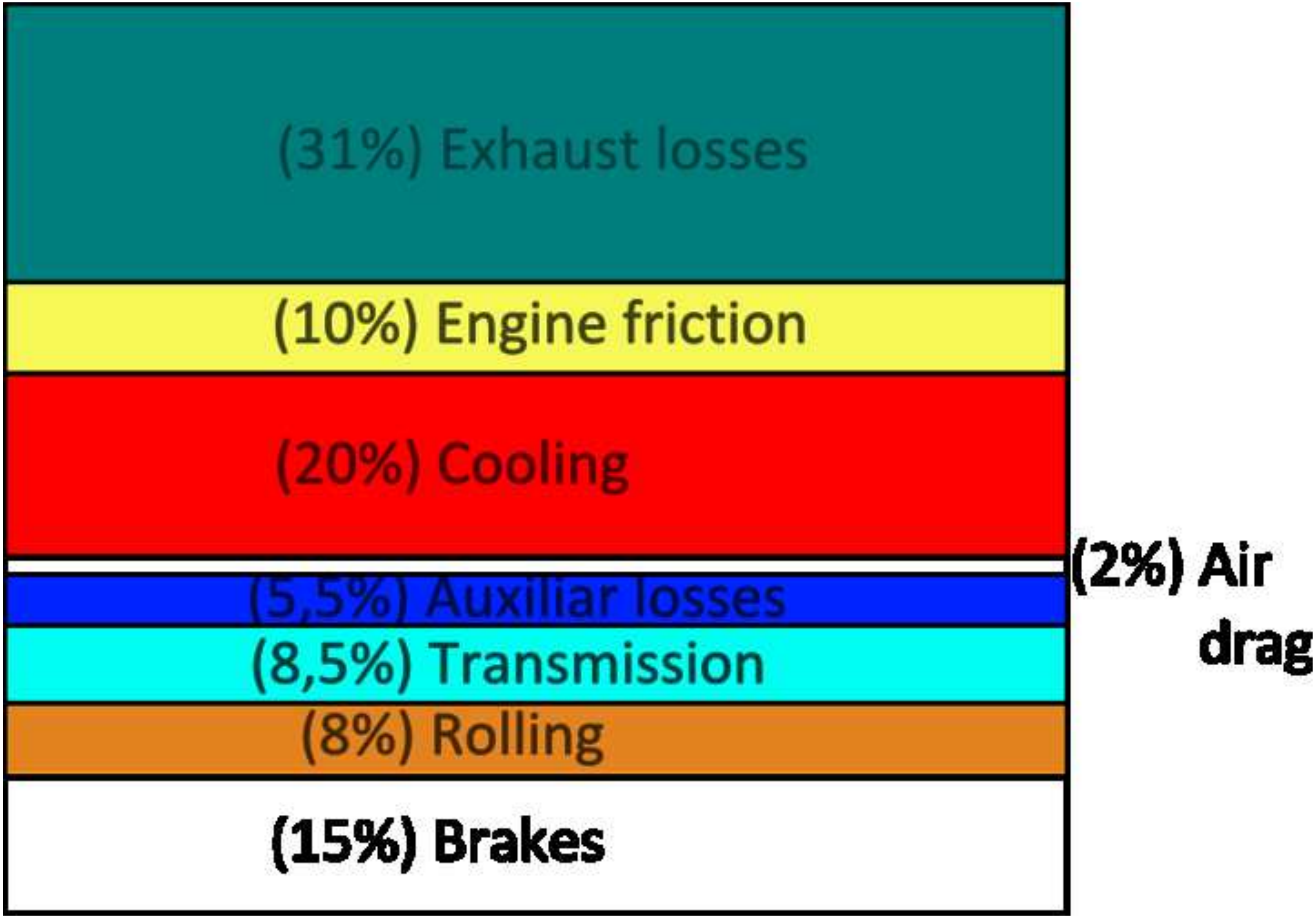
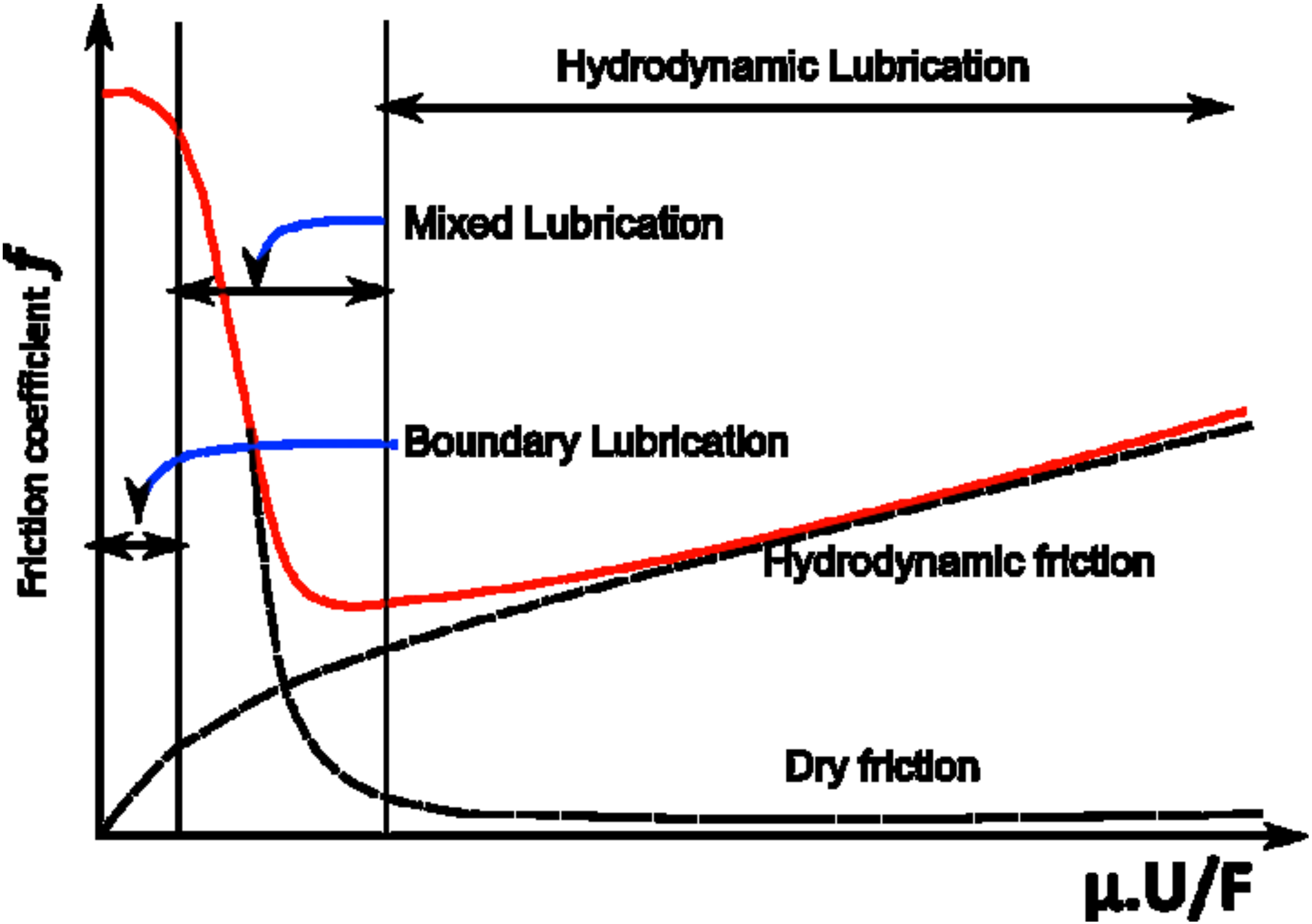


Figure2_color




Hydrodynamic Lubrication
Mixed Lubrication
Boundary Lubrication
Hydrodynamic friction
Dry friction
Friction coefficient *f*
μ.U/F

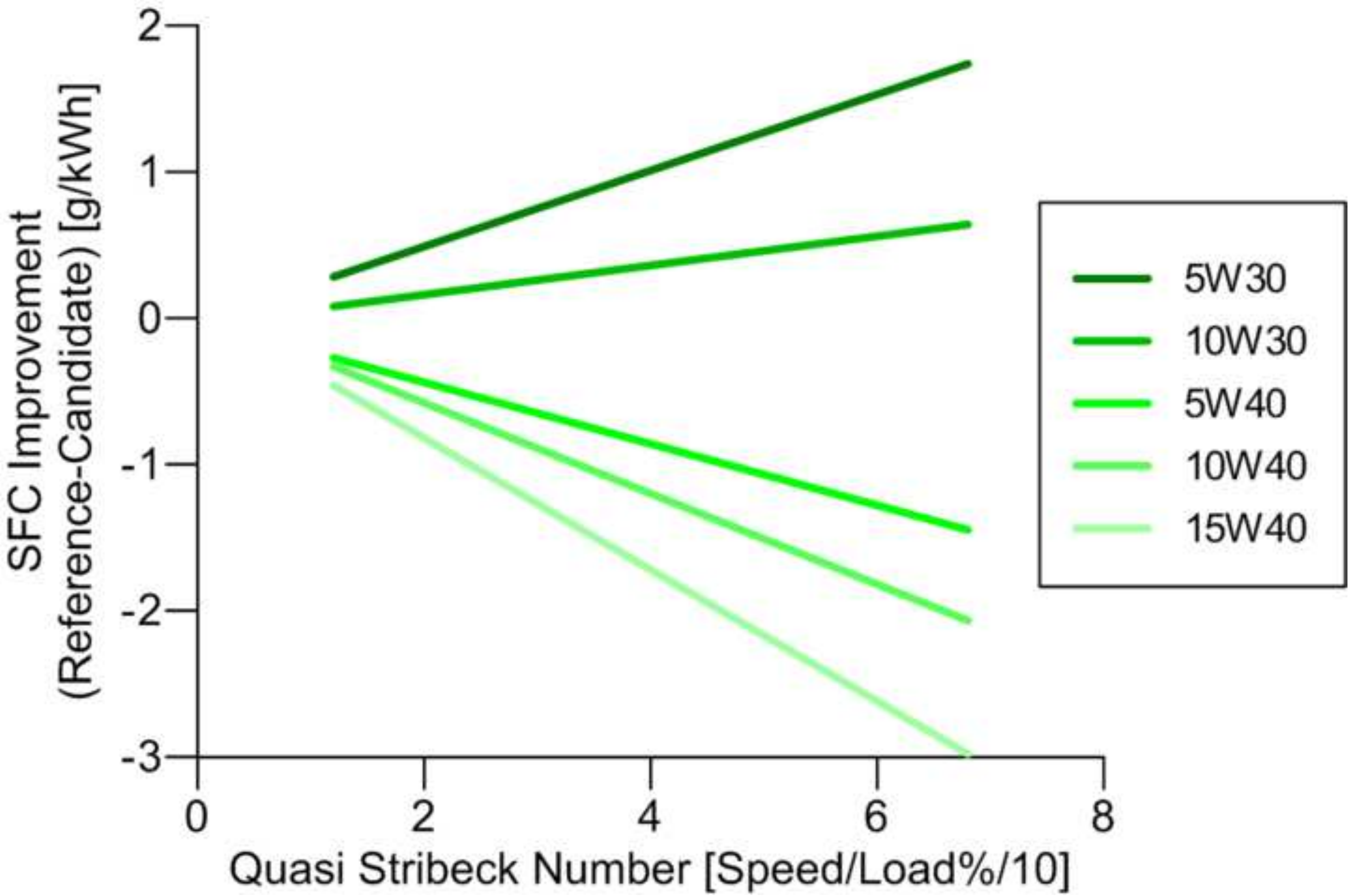
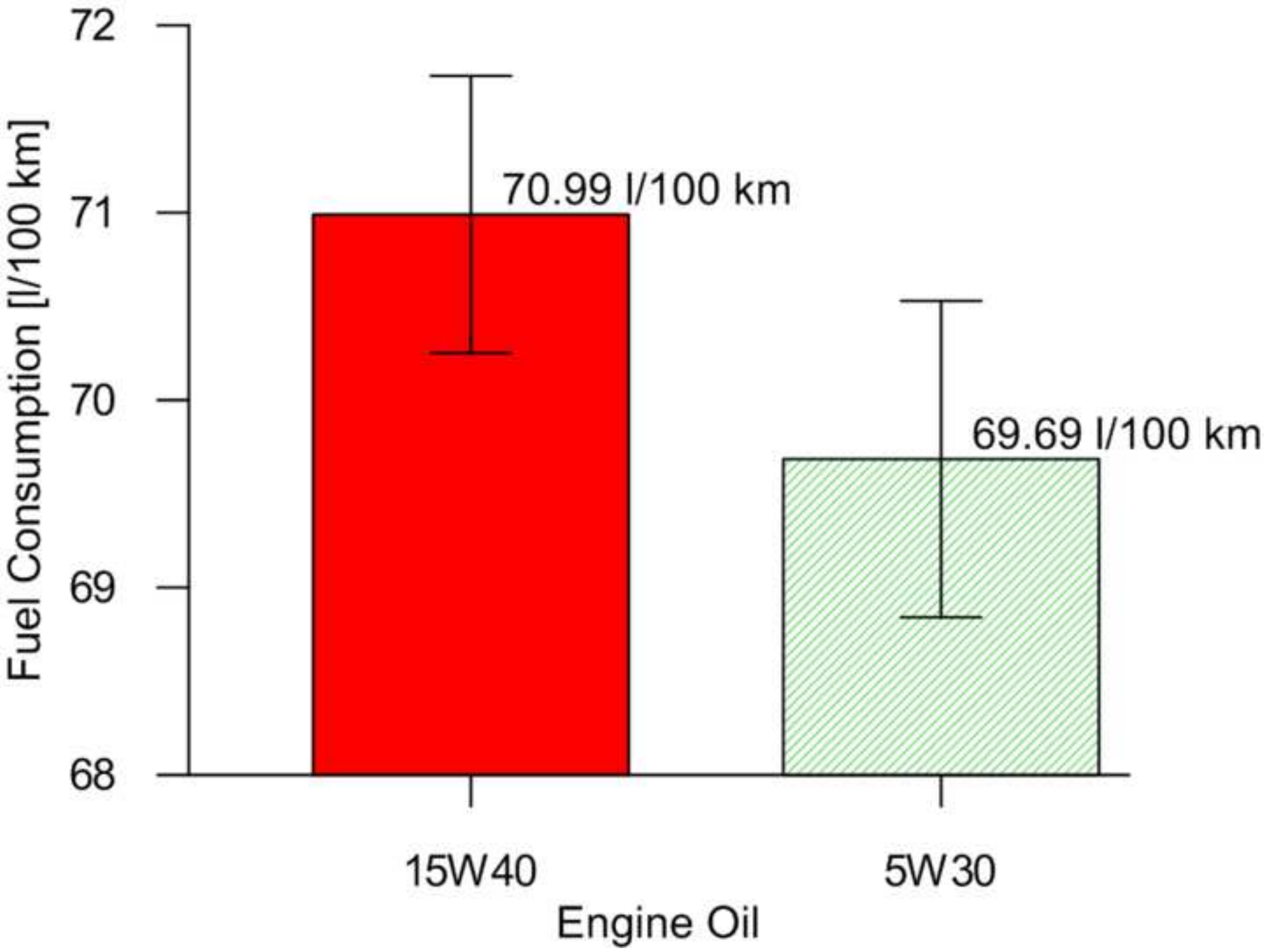

SFC Improvement
(Reference-Candidate) [g/kWh]
2
1
0
-1
-2
-3
0
2
4
6
8
Quasi Stribeck Number [Speed/Load%/10]
5W30
10W30
5W40
10W40
15W40

Figure5_color



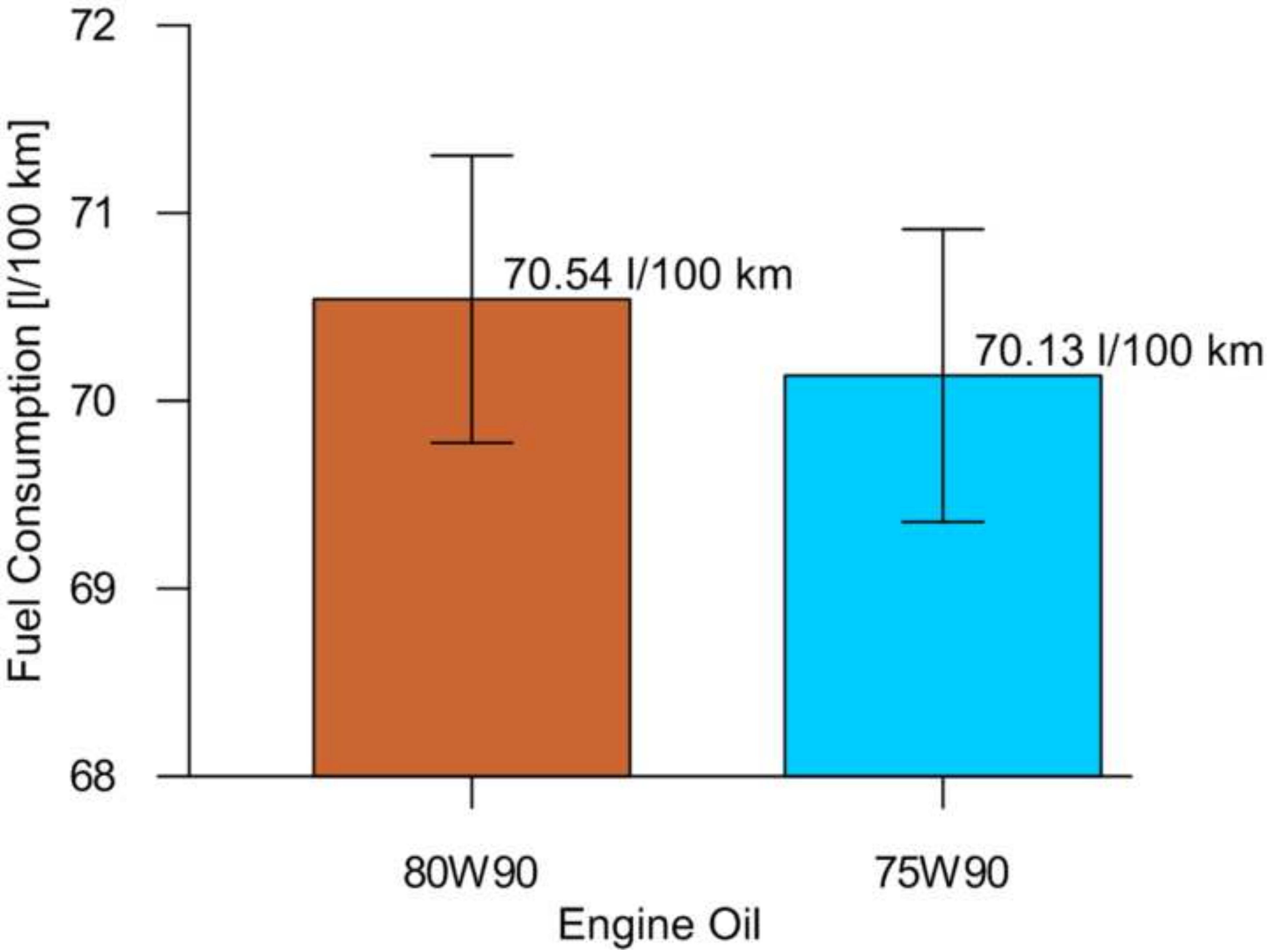

72
71
70
69
68
Fuel Consumption [l/100 km]
70.54 l/100 km
70.13 l/100 km
80W90
75W90
Engine Oil

Figure7_color

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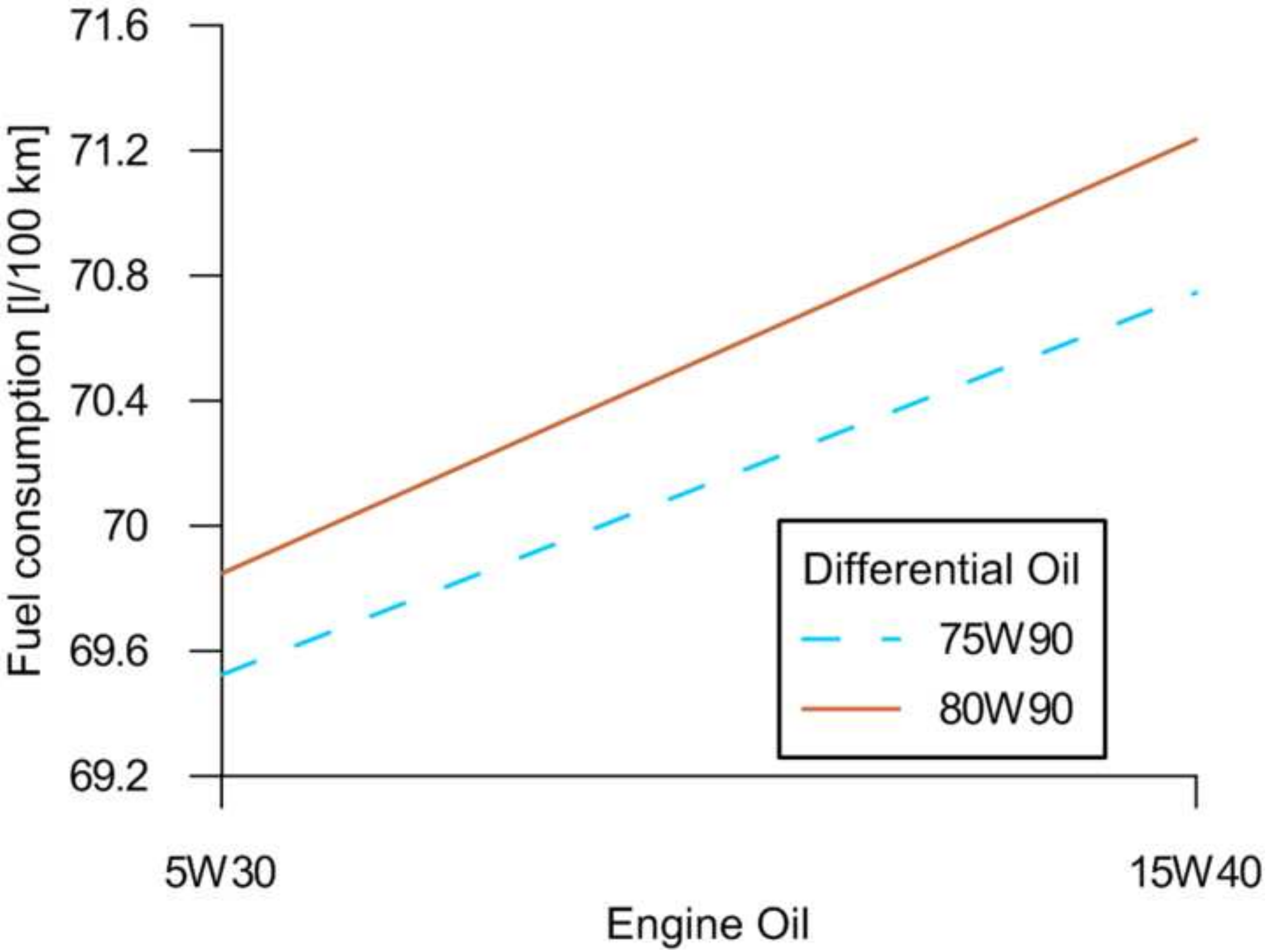
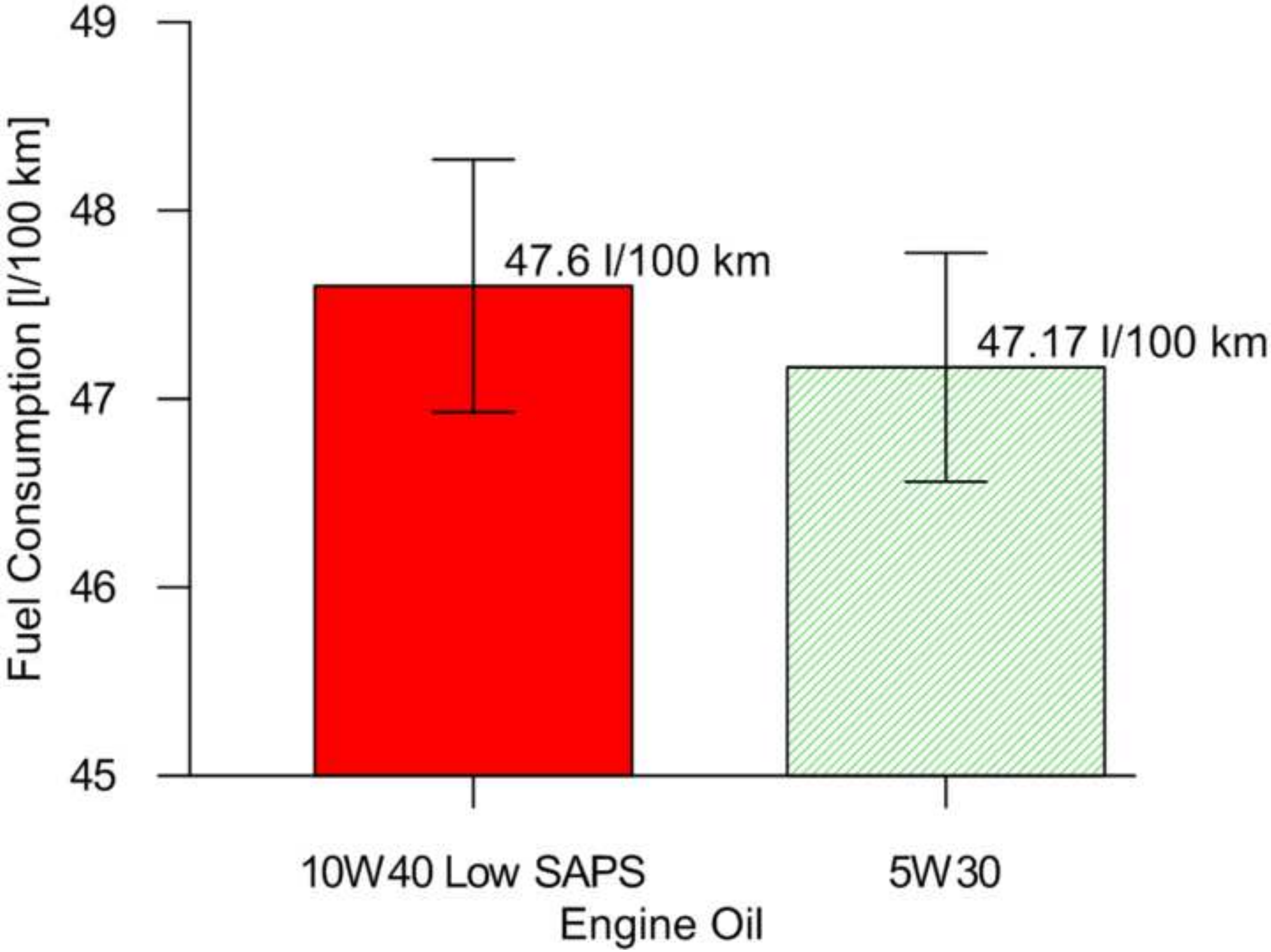



49
48
47
46
45
Fuel Consumption [l/100 km]
47.6 l/100 km
47.17 l/100 km
10W40 Low SAPS
5W30
Engine Oil

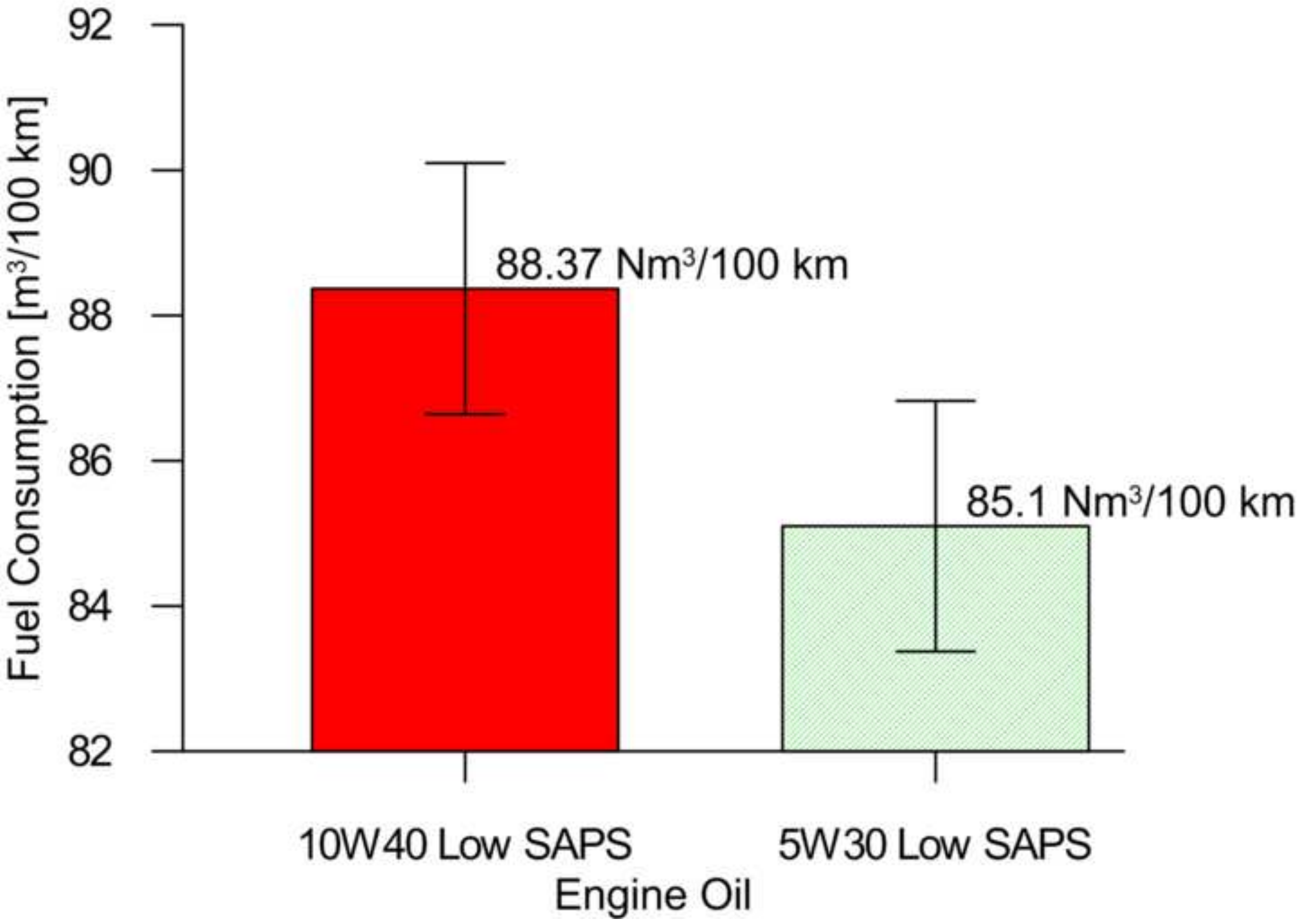
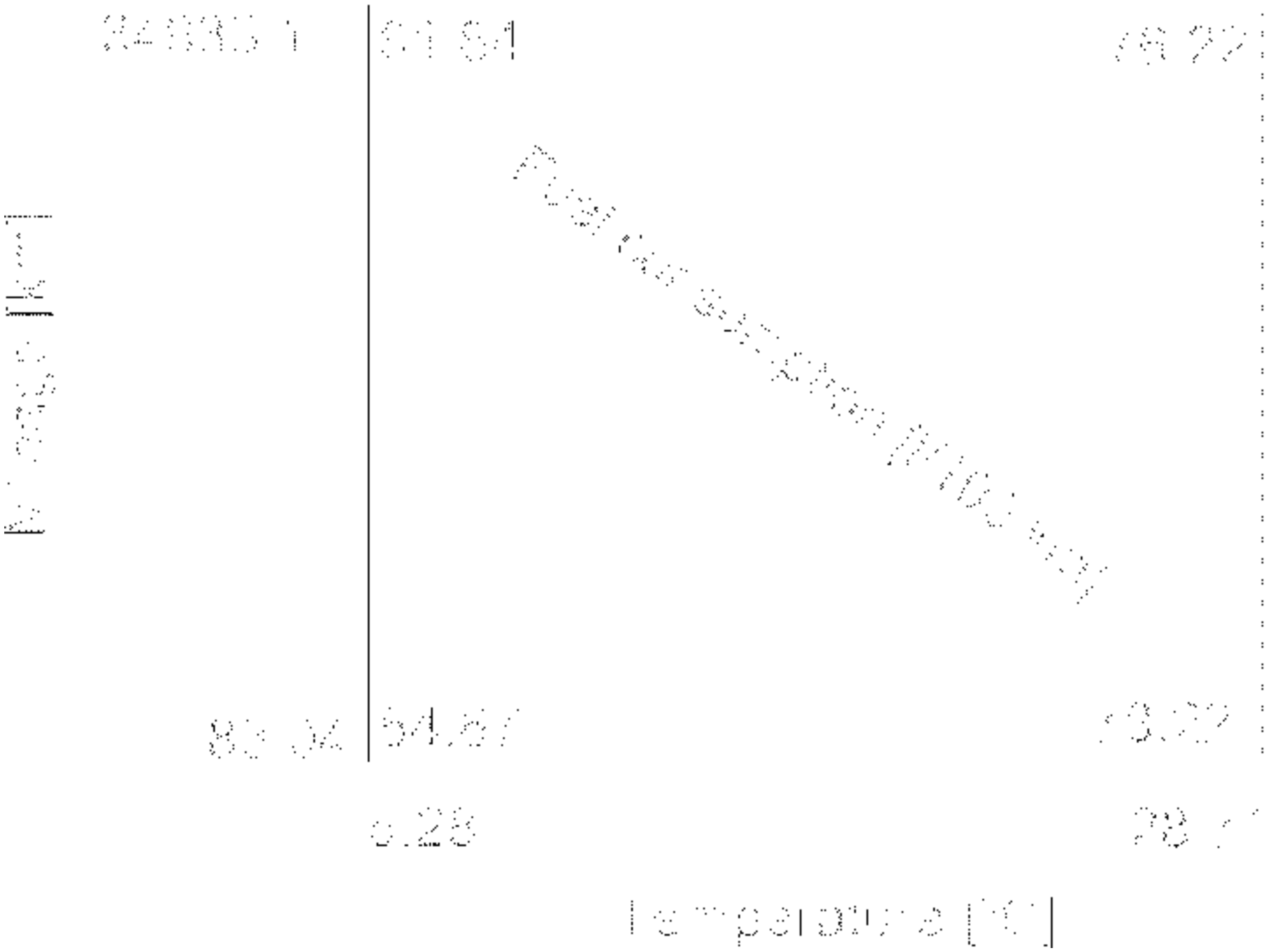

92
90
88
86
84
82
Fuel Consumption [m³/100 km]
88.37 Nm³/100 km
85.1 Nm³/100 km
10W40 Low SAPS
5W30 Low SAPS
Engine Oil

Figure10_color



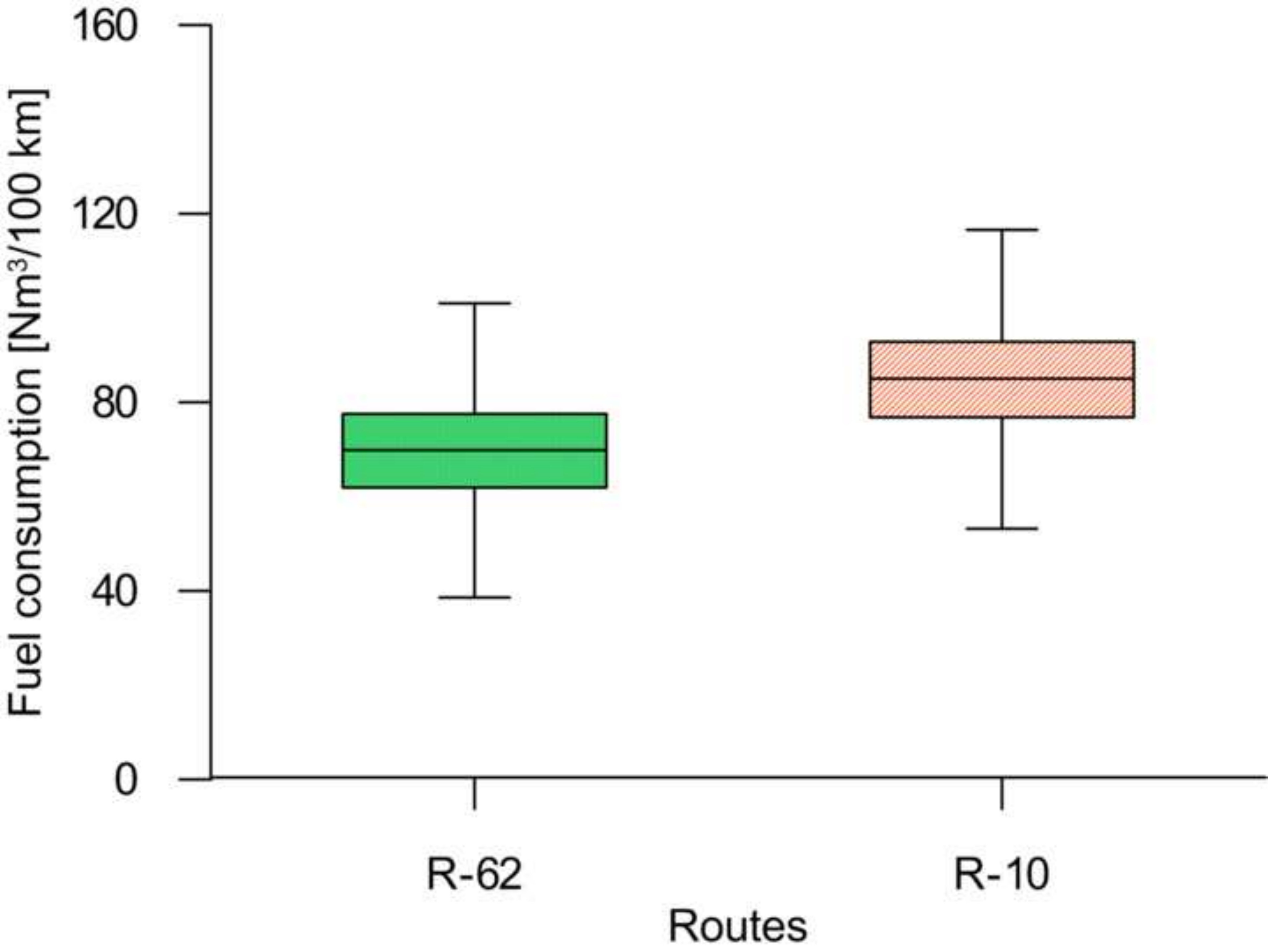

160
120
80
40
0
Fuel consumption [Nm^3/100 km]
R-62
R-10
Routes

Figure12_color