CRANFIELD UNIVERSITY

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AN INVESTIGATION INTO WHETHER A BTCC RACING CAR CAN BE SHOWN TO EMIT NO MORE CARBON DIOXIDE THAN ITS SHOWROOM EQUIVALENT

SCHOOL OF APPLIED SCIENCES

M.Sc. THESIS

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Abstract

The British Touring Car Championship’s emissions initiative aims to demonstrate a BTCC racing car can emit no more CO_2 than its showroom equivalent, (the standard road car that racing cars are based upon) for publicity purposes. This research project investigates options, which might achieve this aim, although this may not be possible. A series of initial concepts were considered and rejected.

A drive-cycle option was investigated. Well-known, existing drive-cycles were considered unsuitable in the present context as unlikely to provide the desired results. In-race operating conditions data for a typical BTCC racing car was collected and analysed for drive-cycle development. Further data was collected on the specifications and performance of a BTCC racing car and its showroom equivalent. The cars’ CO_2 emissions were subsequently estimated. Statistical analysis was carried out on the in-race operating conditions data. The BTCC race data commonly included operating conditions beyond the limitations of the BTCC’s dynamometer and the racing cars showroom equivalent.

Under wide-open throttle operation at steady engine speeds between 5500rpm and 6000rpm, the mass of CO_2 emitted per second, by a BTCC racing car, is predicted to be less than that emitted by its showroom equivalent under the same conditions. However, since these engine speeds are infrequently reached during BTCC races such a comparison could be open to criticism through

focussing on unrepresentative data. Further, such an emissions ‘window’, may not apply to all BTCC racing cars and their respective showroom equivalents. At corresponding points across a range of race representative engine speeds (5500-8500rpm for the racing car and 3500-6000rpm for the showroom equivalent), under wide-open throttle operation, steady engine speed emissions tests are predicted to show the BTCC racing car emitting a similar or lesser mass of CO_2 per kWh than its showroom equivalent. This last comparison is the recommended solution.

Executive Summary

In 2007 The British Touring Car Championship launched an Emissions Initiative, to promote the series as environmentally responsible, one objective of which involves demonstrating that BTCC racing cars can emit no more Carbon Dioxide (CO_2), than their showroom equivalents. The research attempted to locate a method, to demonstrate this, although this might not have proved possible. The project's aims were defined as:

1. Identify the fundamental aspects of CO_2 emissions in current BTCC cars and their showroom equivalents
2. To develop a number of methods for comparing the cars' CO_2 emissions
3. Identify any method(s) likely to provide the series with the results it seeks

Existing literature finds that CO_2 is produced in internal combustion engines when hydrocarbon fuels oxidize in the combustion chamber and additionally when particular constituents of untreated exhaust gas pass through a functioning catalytic converter. The mass of CO_2 emitted to the atmosphere as a result, is directly related to the mass of fuel used.

A series of methods for comparing the cars' emissions were considered and rejected as unsuitable.

Drive-cycles simulated by dynamometers are used by regulatory authorities to regulate and compare emissions and fuel consumption for motor vehicles, and

therefore offer a potential solution to the BTCC's needs. Well-known existing road driving drive-cycles including the Modified New European Drive Cycle are unsuitable in the BTCC context, incorporating operating conditions for which the road cars are likely to be designed to minimise fuel consumption (and therefore CO2 emissions). The racing car is conversely is designed for performance and would under such conditions consume a greater mass of fuel (emit a greater mass of CO2 than the road car, thus failing to provide the results sought. It was proposed that a bespoke drive-cycle, based on typical BTCC race operating conditions, be investigated.

Data was collected on the specification and power output of a typical BTCC racing car and its showroom equivalent, together with data on the in-race operating conditions of a typical BTCC racing car. Instantaneous fuel consumption estimates for both the road and racing car were calculated across the cars' respective operating ranges.

Race data descriptive statistics suggest that in-race deceleration is beyond the limits of the BTCC's dynamometer and that much of the acceleration is beyond the road car's capabilities. Thus applying a single drive cycle to the road and BTCC racing car reflecting BTCC race operating conditions was not a feasible option.

The instantaneous fuel consumption estimates suggest that running both cars at identical steady engine speeds, between 5500rpm and 6000rpm with the throttles wide open, would result in the racing car emitting a similar or lesser mass of CO_2 per second, than its showroom equivalent. Such a ‘window’ may not exist in the case of other BTCC racing cars and showroom equivalents, and this narrow range of engine speeds is open to criticism for being unrepresentative of typical BTCC racing car in race operating conditions.

The brake specific fuel consumption estimates suggest that at corresponding points, under wide-open throttle operation, above the mid-point of each car’s engine speed operating range, (i.e. above 3500rpm and 5500rpm in the road and racing car respectively) the racing car has a lower specific fuel consumption, than its showroom equivalent, irrespective of the latter’s aspiration method.

It is recommended that tests be carried out to confirm the accuracy of the brake specific fuel consumption estimates. If, as expected, they confirm the findings of the report, an emissions test based upon a series of engine speeds within the aforementioned range, should be developed to compare the fuel consumption (CO_2 emissions) efficiency of BTCC racing cars and their showroom equivalents, for publicity purposes and as a pre-season homologation test.
The research has located a method, basis and area for further investigation by the BTCC’s Technical Team and has directed them towards a solution for proving publicly, that a BTCC racing car can emit no more CO_2 than its showroom equivalent.

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Nomenclature

Al_2O_3	Aluminium Oxide
BSFC	Brake Specific Fuel Consumption
BTCC	British Touring Car Championship
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ECU	Electronic Control Unit
FIA	Federation Internationale d'Automobiles
FTP	Federal Test Procedure
H_2O	Water (Vapour)
HC	Hydrocarbon
kg	Kilogram
kmh^{-1}	kilometre(s) per hour
kW	Kilowatt(s)
kWh	Kilowatt Hour
Lambda (λ)	Excess Air Factor in the Air Fuel Mixture
MOT	Ministry of Transport
MNEDC	Modified New European Drive Cycle
NO_x	Nitrous Oxide(s)
N_2	Nitrogen
O_2	Oxygen
RPM	Revolutions Per Minute
ToCA	Touring Car Association

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1.0 Introduction

Following UK Government[1] and Automotive Industry initiatives[2] to reduce motor-vehicle Carbon Dioxide (CO_2) emissions, the British Touring Car Championship (BTCC) has launched its own CO_2 emissions reduction initiative[3], which aims to generate publicity by promoting the championship as being environmentally responsible[3]. The publicised intention is for BTCC racing cars to emit no more CO_2 than the equivalent showroom model upon which they are based[3]. The BTCC's technical team seek a methodology, which shows that under certain circumstances the two cars can emit the same mass of CO_2, thus enabling publicity activities to go forward. This project investigates the fundamental aspects of the production of CO_2 in the series, and whether and how the above aim might be attained.

1.1 Project Aim

To develop methods and quantify how CO_2 is produced by cars in the BTCC series. The methods should be suitable for producing publicity material if results show an advantage in the current case.

1.2 Project Objectives

1 To identify the fundamental aspects of CO_2 emissions in current BTCC cars and their showroom equivalents

2 To develop a number of methods for comparing the CO_2 emissions of the cars

3 Identify any method(s) likely to provide the series with the results it seeks

2.0 A BTCC Racing Car and Showroom Equivalent

To be eligible to compete in the British Touring Car Championship, a racing car must comply with the series' regulations, which at the time of writing include the FIAs S2000 regulations[4,5] and the BTCC's own Sporting Regulations[6]. For a detailed list of specifications, the reader is referred to these documents.

BTCC racing cars must be based upon the body and basic engine of four-seat versions of 'standard' production road cars (minimum build quantities apply[6]). The specific standard models are shown within the homologation documentation, supplied to the BTCC's Technical Team by each racing team[7]. This document includes information on the modifications made to the standard car, which convert it to a BTCC compliant racing car.

Table 1 below, highlights notable differences between the standard (2005 on) Vauxhall Vectra SRi 2.0T and 888 / VX – Racing's 2008 Vauxhall Vectra BTCC racing car. It is these differences, which suggest that the mass of CO_2 emitted by the two cars might be dissimilar. A comparative test is sought, which would demonstrate parity between the cars' emissions. Locating such a comparative test is the purpose of this research.

Table 1. Comparing Specifications of a BTCC Racing Car and its Showroom Equivalent

	Standard SRi 2.0i T Vauxhall Vectra	888 / VX – Racing 2008 Vauxhall Vectra
Peak Engine Power Output (kW)	129 @ 5500rpm[8] 121 @ 5518rpm[9]	~200 @ >8000rpm[10]
Mass (kg)	1456 (excl. Driver)[8]	~1200 (incl. Driver)[6]
Track	Standard[8]	Non-standard[7]
Tyres	235 / 35 R19[8]	Dunlop 235 / 610 R17 ‘slicks’[6]
Rear Aerodynamic Device	Standard ‘Lip’ Boot Spoiler[8]	BTCC Authorised Device[6]
Suspension	Standard units[8]	Non-Standard units[7]
Brakes	Standard units[8]	Non-Standard units[7]
Gearbox	Standard unit[8]	Non-standard sequential unit[7]
Catalytic Converter	Standard unit[8]	Non-standard racing variant[11]
Traction Control	In use[8]	Disabled[5]
Electronic Control Unit	Standard[8]	Pectel SQ6M[12]
Bodywork	Standard[8]	Non-standard wheel arch extensions and front panel[7]
Air Fuel Ratio	Lambda 1 (est.)[2]	Lambda 0.85 – 0.9[13]

3.0 Carbon Dioxide Formation in the Internal Combustion Engine

Both the BTCC's racing cars and the standard road car they are based upon, are powered by gasoline fuelled four stroke internal combustion engines[6,8], a detailed description of the operation of which can be found in a standard text such as Stone[14].

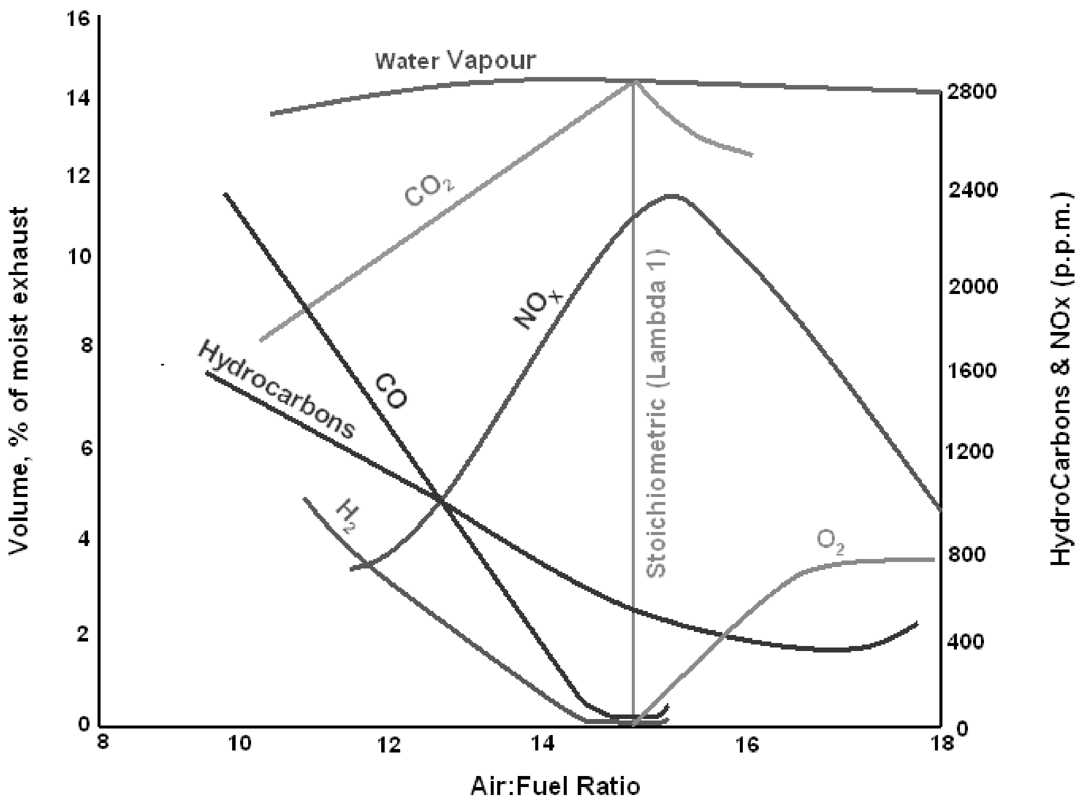
Put simply, hydrocarbon fuel is mixed with air, (forming the charge) which when enclosed within the combustion chamber, is oxidized. The oxidization converts chemical energy stored in the fuel into heat, sound and kinetic energy[2]. The latter causes the crankshaft to rotate and the car to be propelled and its ancillaries to be powered[2]. It follows that, the greater the energy needed to propel the car and power the ancillaries, the greater the amount of fuel burned to release that energy.

Carbon Dioxide (CO_2) forms as the hydrocarbon fuel in the charge oxidizes[2]. The chemical equation being:

$n_1\ C_xH_y$	+	$m_1\ O_2$	$\rightarrow$	$n_2\ H_2O$	+	$m_2\ CO_2$
(Fuel)		(Oxygen)		(Water Vapour)		(Carbon Dioxide)

In order that all the fuel is converted to H_2O and CO_2, the charge should contain precisely the mass of air required to completely oxidize it[2]. For gasoline the theoretically correct (stoichiometric) air mass-fuel mass ratio is 14.7:1[2]. This theoretically correct air mass-fuel mass ratio has no excess air in the charge, and is said to have an excess air factor (lambda) of 1[2]. Lambda > 1 and <1 denote charges containing excess air and excess fuel respectively[2]. The effects of varying the air-fuel ratio in the charge on the composition of the untreated exhaust gas can be seen in Figure 1 below.

Figure 1 – The Relationship between Exhaust Gas Composition and the Air-Fuel Ratio[15]

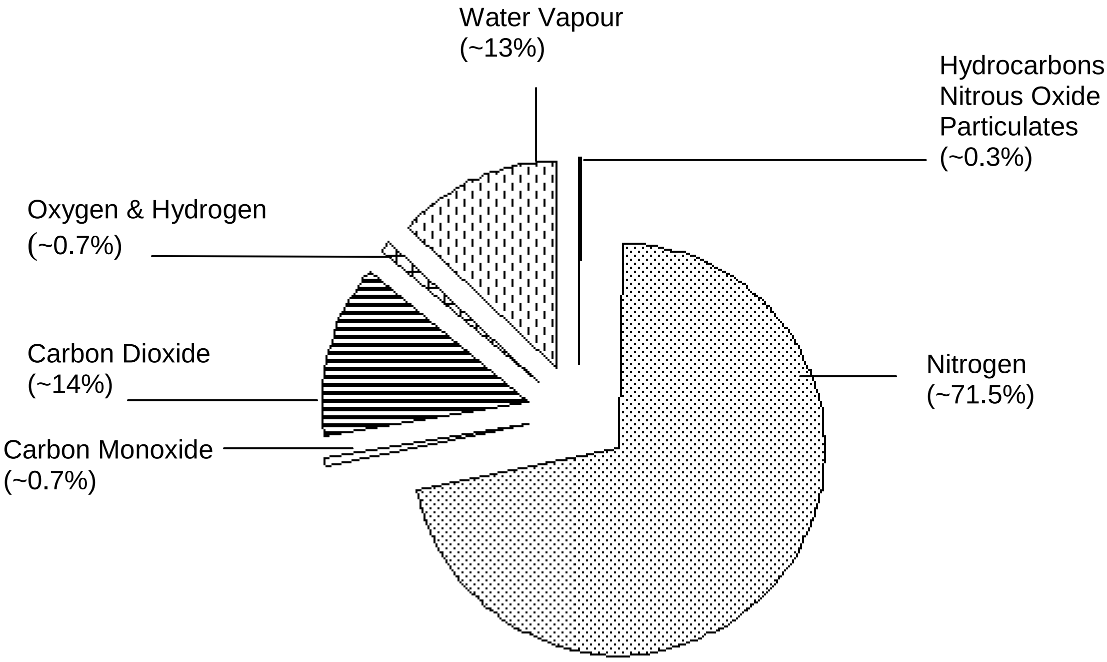


In the engines in question, an air mass sensor located in the inlet ducts, measures air mass flow rate into the engine and the electronic control unit (ECU) subsequently calculates the fuel mass to be added, to achieve the desired air-fuel ratio[2]. This is admitted to the inlet manifold or the combustion chamber itself, through the use of fuel injectors[2]. The duration of injector operation controls the amount of fuel delivered in each pulse[2].

Modern systems continuously adjust the injection timing through closed loop control[2]. Lambda sensors (electrochemical devices, whose potential difference varies with changes in the concentration of oxygen in the exhaust gas) provide feedback of the results of the ECU calculations[2]. Traditional lambda sensors are used as “transition” devices; when the mixture is “lean” the ECU progressively increases the amount of fuel added to the charge until the lambda sensor signals insufficient oxygen in the exhaust gas[2]. The ECU then progressively reduces the amount of fuel in the mixture until the lambda sensor detects too much oxygen in the exhaust gas and the cycle then starts again[2]. More recent systems have the option of improved wide-band lambda sensors that can measure oxygen concentration more directly and allow more rapid changes in fuel rate to maintain combustion efficiency[2].

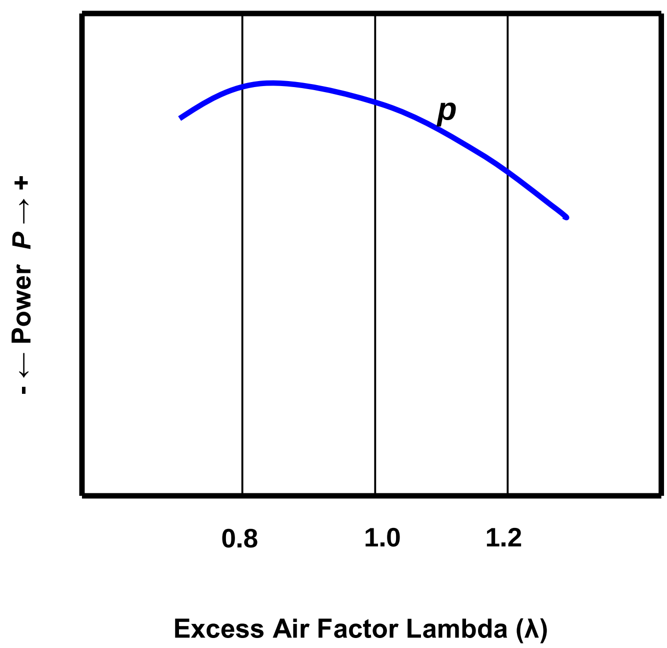
The above process means that the air-fuel ratio oscillates (albeit within a narrow range) around the target air-fuel ratio[2]. The target air-fuel ratio for road cars (showroom equivalents) using homogeneous charges in the combustion chamber is typically lambda 1[2] to minimise concentrations of Carbon Monoxide (CO), Hydrocarbons (HCs) and Nitrogen Oxides (NO_X), ‘pollutants’ that are subject to legislative restrictions[16]. The composition of untreated exhaust gas resulting from a charge of lambda 1 would be as per Figure 2 below.

Figure 2 – Composition of Untreated Exhaust Gas at Lambda 1[17]



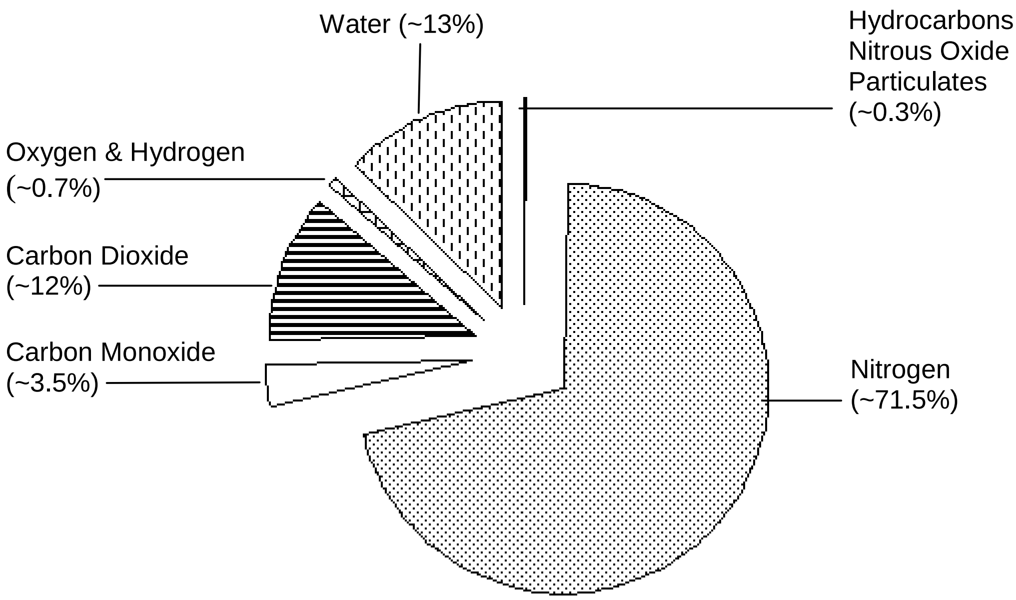
A BTCC racing car's target lambda factor is between 0.85 and 0.9[13], to optimise the engine's power output in relation to the air-fuel ratio (see Figure 3 below).

Figure 3 – The Relationship between Power and the Air-Fuel Mixture[2]



Consequently, the racing cars' raw exhaust gas contains higher concentrations of CO and HCs and lower concentrations of CO_2 than the equivalent road car. The concentration of gases in the untreated exhaust gas is as in figure 4 below.

Figure 4 – Composition of Untreated Exhaust Gas at Lambda 0.9[17]



3.1 Exhaust Gas After-Treatment

Both the showroom model and the BTCC racing car are fitted with catalytic converters located in the exhaust pipe[6,8]. Catalytic converters contain ceramic or metallic monoliths[2]. These monoliths have Aluminium Oxide coated passages running through them[2]. The Aluminium Oxide increases the surface area over which the exhaust gas passes[2]. The catalysts themselves typically consist of platinum, palladium and rhodium.

Once the catalytic converter is heated to 300˚C by the passing exhaust gas, it begins to oxidise it[14]. Modern three-way catalytic converters, operate in two stages[14], the first of which oxidizes Carbon Monoxide and hydrocarbons[14] as follows[2]:

$2CO$	+	O_2	→	$2CO_2$
Carbon Monoxide	+	Oxygen	→	Carbon Dioxide

$2C_2H_6$	+	$7O_2$	→	$4CO_2$	+	$6H_2O$
Hydrocarbons (Fuel)	+	Oxygen	→	Carbon Dioxide	+	Water

The second stage reduces NO_X emissions as follows[2]:

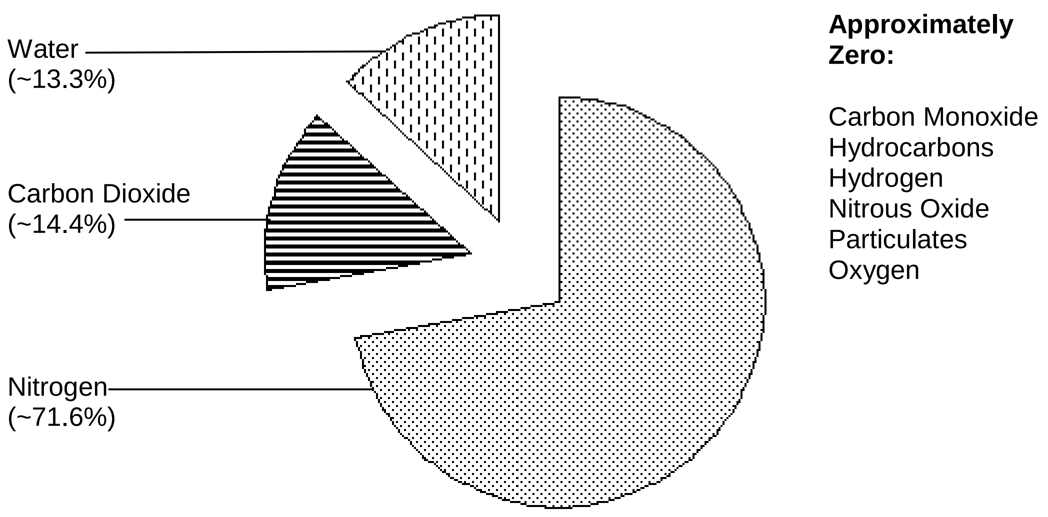
$2NO$	+	$2CO$	→	N_2	+	$2CO_2$
NO_X	+	Carbon Monoxide	→	Nitrogen	+	Carbon Dioxide

$2NO_2$	+	$2CO$	→	N_2	+	$2CO_2$	+	O_2
NO_X	+	Carbon	→	Nitrogen	+	Carbon	+	Oxygen

Monoxide Dioxide

Optimal conversion of the pollutants (almost all of them) by the catalytic converter requires an air-fuel mixture in chemical balance (lambda 1), making lambda closed loop control essential for minimising the aforementioned "pollutants" [2]. However, under sub-optimal conditions, i.e. deviations from lambda 1, catalytic converters still convert approximately 98% of pollutants[2]. Employing catalytic converters means nearly all the fuel is oxidized and converted into water and carbon dioxide. The composition of the treated exhaust gas would be as per Figure 5 below.

Figure 5 – Composition of Exhaust Gas After Treatment by a Catalytic Converter[17]



The chemical equations above, determine the ratio of components consumed and produced. As this is fixed, the total mass of components produced depends directly on the mass of fuel and oxygen burnt. From this it follows that the amount of CO_2 emitted from a car is directly related to its fuel consumption[2].

Having determined how an internal combustion engine produces CO_2, the next stage is to consider options for comparing the CO_2 emissions (or fuel consumption) of a BTCC racing car and its road going counterpart.

4.0 Comparison Methods for Measuring CO_2 emissions

4.1 Racing Laps

4.1.1 The Concept

This method compares the total mass of CO_2 emissions from a BTCC racing car and its showroom equivalent generated by completing a series of fast laps, starting and finishing at rest.

4.1.2 Analysis

The work done by the engine determines the amount of fuel consumed, and in turn the mass of CO_2 produced. Thus a comparison of the energy delivered to both road and racing cars during the laps provides an indication of the relative mass of CO_2 emitted therein.

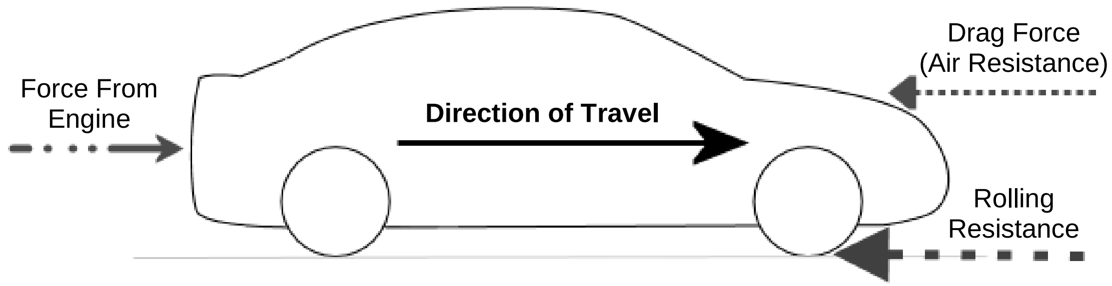
The energy needed to move a car could be broken down into:

The energy required to:

1. Move the mass of the car itself (the energy converted into kinetic energy);
2. The energy required to overcome the drag force generated by the air
3. Rolling Resistance[18]

See Figure 6 below.

Figure 6 – The Key Forces Acting on a Moving Car[18]



1. Energy required moving the mass of the car

When a car accelerates, the engine power is converted into kinetic energy in the moving mass[2]. This energy is constant while the speed is constant[18] ($E=1/2\ mV^2$), and is then lost to heat in the brakes (or rolling/aerodynamic losses if coasting) as the car decelerates[18], it is not regenerated or stored[5].

As the cars start and ultimately finish the comparison at rest, all of the kinetic energy in the moving mass is lost to heat[18]. Therefore, regardless of the mass differences between the cars, the faster the lap time the greater the loss of energy overall[18]. This effect is increased by the frequent acceleration and deceleration of any car on a racing lap.

As a general rule, the racing brakes fitted to BTCC cars dissipate energy more quickly than those on the road car and the racing cars can brake later and from a higher speed when cornering. A greater change in speed equates to a greater loss of kinetic energy at each corner, and greater overall energy input from the engine accelerating between corners. Fundamentally, even when a road car is being driven fast around a track, the racing car will consume more energy doing the same.

2. Energy required overcoming the drag force generated by the air moving over the car

Drag force is calculated using:[18]

$D = ½ C\rho Av^2$

Where:

D = Drag force

C = Coefficient of the object

ρ = Air density

A = Effective cross sectional area (the cross sectional area taken perpendicular to the velocity)

v = Relative speed between the air and the object.

The rear aerodynamic device added to the racing cars is likely to add drag as it generates down-force, making the racing cars' coefficient of drag (C) greater than the road cars' drag coefficient.

The cross sectional area (A), must be higher for the racing car, due to its wider bodywork.

The velocity of the racing car (v), at all points around the track will be greater for the racing car than the road car as determined in the moving mass energy analysis above. Holding the velocity of the air constant, v^2 will be significantly larger for the racing car than for the road car.

If C, A and v^2 are greater for the BTCC car than the showroom model, holding 'ρ' constant, means the drag force acting on the BTCC car is greater than the drag force acting on the road car. The BTCC car thus requires a greater amount of energy to overcome this drag force.

3. Rolling Resistance

The tyres fitted on the racing car are toed out[19] and designed to optimise friction between the tyre and the surface of the racetrack for the duration of a 20-lap race and/or a practice session[20]. The tyres fitted to the road car are not offset[8] and are designed to offer friction over several thousand miles and use a harder compound than that for racing car tyres. Thus the rolling resistance, (the friction force between the tyres and the road) is likely to be greater for the racing car; however, the difference is unlikely to be significant.

The greater resistive forces (drag and rolling resistance) acting against the forward motion of the racing car means a similarly greater amount of energy is needed to overcome them. Combined with the greater amount of kinetic energy involved in the racing cars lap, the total energy used by the racing car must be greater than that used in the road car. Consequently the total fuel consumption and therefore the total CO_2 emissions of the racing car must be significantly higher.

4.1.3 Recommendation

A comparison of the total CO_2 emissions of the racing car and its showroom equivalent completing a series of racing laps, would not show the BTCC car as emitting the same mass of CO_2 as its showroom equivalent. This method of comparison would not provide the series with the publicity it seeks and therefore cannot be recommended.

4.2 Catalytic Converter Removal

4.2.1 The Concept

A comparative test as above is carried out, this time with the racing car's catalytic converter removed from the exhaust system to reduce the mass of CO_2 emitted from the BTCC racing car.

4.2.2 Analysis

From the combustion analysis above, removing the catalytic converter from the exhaust system would reduce the concentration of CO_2 in the exhaust emissions of the racing car, and consequently the total quantity emitted. This is a simple and inexpensive method for reducing the mass of CO_2 emitted by the racing car.

The concentration of CO_2 in treated exhaust gas is approximately 14% (depending upon ambient conditions[2]). The concentration of CO_2 in untreated exhaust gas for the racing car, at lambda 0.9 would be approximately 12%[17]. The mass of CO_2 emitted by the racing car will be significantly greater than the road car, such that a 2% reduction in the concentration of CO_2 in the racing car's exhaust gas will still not provide results which show the cars as emitting similar masses of CO_2.

Further, removing the catalytic converter would result in the BTCC car emitting greater masses of CO, HC's and NO_X.

4.2.3 Recommendation

Removing the catalytic converter from the BTCC car would not provide the results sought by the BTCC Technical Team. The associated increase in harmful pollutant emissions, contradicts the environmentally responsible image the BTCC is attempting to portray. Thus this option cannot be recommended.

4.3 Regenerative Braking

4.3.1 The Concept

This concept involves both cars completing a set of racing laps as per the first comparison methodology. In this variation, the BTCC racing car is fitted with a regenerative braking system, which stores energy, normally transferred to the brakes and lost to heat, for later use[21].

4.3.2 Analysis

Ignoring questions over the feasibility of developing a system for a BTCC car within their preferred time frame, (prior to the 2009 season start) the attendant expense involved, the safety considerations and the usefulness of such an option remains in doubt. The addition of this system to a BTCC racing car would constitute a significant alteration to that car such that it would not be representative of BTCC racing cars in general. (There are no plans for 2009 cars to employ regenerative braking[22].) Thus the comparison would be between a non-standard BTCC racing car and its showroom equivalent.

4.3.3 Recommendation

The fitting of a regenerative braking system to a BTCC car would constitute a significant modification. Any subsequent comparisons of CO_2 emissions would not be (as is required) between a ‘standard’ road car and a ‘standard’ BTCC car. Regardless of any feasibility issues, this option cannot be recommended.

4.4 An ‘MOT’ Style Emissions Test

4.4.1 The Concept

Test both cars according ‘MOT’ Emissions Test using a certified gas analyser. Should the racing car pass the test, it could be claimed that its emissions are on a par with the showroom model.

4.4.2 Analysis

Certified gas analysers are commonplace as a necessity in MOT stations across the country. Further, their use should be inexpensive, since a full MOT test costs only £54.00[23]. Testing of both cars using this method would be affordable and feasible within the BTCC time and financial constraints. It is also an emissions measurement that is meaningful to the general public.

The MOT emissions test measures concentrations of Carbon Monoxide and Hydrocarbons in the exhaust gas emitted to air, to ensure they are below permissible limits[24]. It does not measure Carbon Dioxide emissions.

Early confidential test results, suggest that a BTCC racing car would not pass the hydrocarbon element of a standard MOT pollutant emissions test[22] although this may be due to the relatively low engine speed during this test.

4.4.3 Recommendation

The absence of a CO_2 measurement fails to directly support the BTCC's emissions publicity programme, although it could support useful emissions related publicity. The confidential test results however suggest that even this option is unlikely. Therefore this option cannot be recommended.

4.5 Emissions Profiling

4.5.1 The Concept

Along similar lines to the MOT test, this idea involves profiling the pollutant emissions of both racing car and its showroom equivalent, at specified power output levels, using a dynamometer and emissions testing equipment or a dedicated emissions testing laboratory.

The resulting data on the concentrations of the different exhaust gas components, (CO_2, CO, NO_X and HC's) at specific power outputs could then be mined in the search for a window where the road and racing car are close on emissions or even, where the racing car is better. Positive results could then be used to create positive publicity for the series.

4.5.2 Analysis

The racing cars are neither designed nor set up with emissions reduction in mind, unlike their showroom equivalents. The racing cars' air-fuel ration of lambda 0.85-0.9 is a sub-optimal condition for effective conversion of pollutants into CO_2, suggesting the catalytic converter will be less effective at converting pollutants into CO_2 and H_2O. It is unlikely that under any conditions the racing cars' emissions will be close to, or better, than the road cars' emissions.

4.5.3 Recommendation

Emissions profiling for CO, HCs and NO_X, is of limited use to the BTCC. It offers only supporting emissions related publicity to their CO_2 focussed initiative. While it could be publicised that the concentration of CO_2 emitted by the racing car would be no greater than the showroom equivalent, publicising this is likely to highlight the greater concentrations of pollutants emitted by the racing car, since the chemical equations must balance. This is likely to attract negative publicity for the series, and therefore such a comparison cannot be recommended.

4.6 Annual Emissions

4.6.1 The Concept

Data on the annual distance travelled by both the BTCC racing car and its standard showroom equivalent is combined with the average fuel consumption figures for both cars, to provide an *indication* of the mass of fuel consumed (and therefore the CO_2 generated) in one year. (Volumetric fuel consumption is an indicator only of the mass of fuel consumed, because the volume of a given mass of fuel varies with changes in the ambient temperature[25].)

4.6.2 Analysis

Average fuel consumption data is multiplied by the annual distance travelled, for both 888 / VX Racing's Vauxhall Vectra's in a typical year[26], and a 'standard' (2005 on) Vauxhall Vectra SRi 2.0T[8], to provide an approximate figure for the volume of fuel consumed in one year. The results can be seen below in table 2.

Table 2. Annual Fuel Consumption Estimates for the 2008 Triple Eight/VX Racing Vauxhall Vectra and its Showroom Equivalent

	Average fuel consumption (l/km)	Annual distance travelled (km)	Annual volume of fuel used (l)
888 / VX Racing Vauxhall Vectra (2008)	0.34[26]	~6000[26]	2040
Vauxhall Vectra SRi 2.0T (2005 on)	0.09[8]	~26400[27,28]	2376

The results in table 2, suggest that using this basis of comparison, a standard Vauxhall Vectra SRi 2.0T would consume >300 litres more fuel than the BTCC racing car in one year. This differential is sufficient to indicate that more accurate assessments of fuel consumption, based upon mass, would offer similar results. Such results show that on this basis, the BTCC racing car emits no more CO_2 than its showroom equivalent in a year.

The figures are close enough to each other, to be a meaningful comparison; however this is only one comparison. Data on annual fuel consumptions for other BTCC racing cars is expected to be lower than for 888 / VX Racing, as 888 complete more distance testing than any other team[22], (no specific data was available). However, many of the other teams run cars whose showroom equivalents typically travel less distance annually than the Vauxhall Vectra, by virtue of the former being in different ‘classes’ of car[29]. Further data collection would be needed to determine if such a comparison of fuel consumption / CO_2 emissions between the racing cars and their showroom equivalents were equally favourable.

Whether further investigation is warranted is questionable. For publicity purposes, such a methodology is meaningful to the public, as it relates their own typical CO_2 emissions in a year, to those of a BTCC racing car. It could however highlight the significantly greater (relative to the road car) fuel consumption per km, of a BTCC racing car.

Further its use is limited solely to initial publicity for the series because the BTCC organisers are not permitted by the sport’s governing body the Motor Sports Association to restrict fuel used for testing[22]. The series organisers have the authority to restrict fuel used at race meetings[22]; however this accounts for only 4000 km (1360l of fuel) of the annual 6000 km (2040l) of the 888 / VX Racing cars. The imposition of fuel consumption (CO_2) limits for race meetings, which is in excess of 1000 litres more than the current annual fuel consumption, is effectively no limit at all and would be unlikely to provide the series with the publicity it seeks. It could provide the sort of publicity the series seeks to avoid.

4.6.3 Recommendation

The positive results of the Vauxhall Vectra SRi / 888 VX Racing Vauxhall Vectra comparison might suggest further data collection is warranted, to determine if all other BTCC racing cars annual emissions compare favourably with their showroom counterparts and are proximate enough to be meaningful. However, even though the data collection and subsequent calculations should be within the BTCC's budget for research and its timeframe for publicity activities, the associated risk of highlighting the racing cars' per km fuel consumption make this a risky comparison. Further, since a CO_2 emissions limit based on this comparison would be essentially irrelevant and potentially controversial this basis for comparison cannot be recommended.

4.7 Total Drive Cycle Emissions Mass

4.7.1 The Concept

Both the BTCC racing car and its showroom equivalent are run through an identical ‘Drive Cycle’. The total mass of CO_2 emitted during the drive-cycle is quantified, compared and favourable results used for publicity purposes.

4.7.2 Analysis

A drive-cycle is a chronological series of speed-time data, (typically at 1 second intervals) developed for certain types of vehicle to simulate the driving conditions of specific environments, with the aim of regulating exhaust gas emissions and fuel consumption[30].

Regulatory authorities across the world use standard drive-cycles to provide comparable emissions measurements for different vehicles[2] and enforce statutory emissions limits on road vehicles typically[24]. Drive-cycles are repeatable using a chassis dynamometer[31].

Since the BTCC currently enjoys complimentary use of a chassis dynamometer and seeks to compare competing racing cars’ CO_2 emissions with the showroom equivalent and subsequently enforce a CO_2 emissions limit, drive-cycles appear to suit the present BTCC situation.

What is needed is a drive-cycle that might provide results showing a BTCC racing car and its showroom equivalent emitting no more total mass of CO_2. The drive-cycle currently used in Europe to ensure that passenger cars (including racing cars' showroom equivalents) comply with emissions limits is the Modified New European Drive Cycle[2], (key characteristics of this drive-cycle can be seen in table 3 below).

Table 3.

Key Characteristics of the Modified New European Drive Cycle[2] (MNEDC)

	Conditions Simulated	*Cycle Format*	*Average Speed (kmh^{-1})*	*Maximum Speed (kmh^{-1})*
Urban Sub-cycle	Cold Start, Congested Traffic	Multiple Micro-Trips	18.7	50
Extra-Urban Sub-cycle	Main Roads, Motorway	Single Trip	-	120
Complete Cycle	Urban & Extra Urban Cycles	Mixed	32.5	120

The MNEDC is used amongst other things for determining official fuel consumption figures for a particular car. As a key selling point, it is likely the showroom equivalent is designed and set-up to minimise fuel consumption during this drive-cycle and similar operating conditions. The BTCC racing car has no such fuel consumption concerns. Thus the showroom equivalent will almost certainly emit a lower mass of CO_2 than the racing car during the MNEDC and this drive-cycle would be unsuitable for the BTCC emissions programme.

Other well-known drive-cycles, for example the Federal Test Procedures[2] and the Japanese Test Cycles[2] simulate road driving in the United States and Japan respectively. Since they involve driving conditions not dissimilar to those within the MNEDC, the cycles remain within the operating range for which the showroom equivalent's fuel consumption is minimised. Thus they also offer little prospect of favourable test results for a BTCC racing car against its showroom equivalent.

To achieve the desired results, a drive-cycle is needed for which the racing car is optimised and the showroom equivalent is not.

4.7.3 Recommendation

Operating conditions where the racing car can function efficiently should be determined, and options for drive-cycles based upon such conditions investigated. This is the aim of the subsequent research.

5.0 Objectives

The British Touring Car Championship aims to promote itself as environmentally responsible[3], through imposing a CO_2 emission limit on cars competing in the championship from 2009. The ultimate aim is to demonstrate BTCC racing cars emit no more CO_2 than the road cars they are based upon[3]. A methodology is sought which is usable as a pre-season homologation test permitting entry to the series and beforehand to demonstrate that both road and racing cars can emit the same quantity of CO_2. A drive-cycle emissions test appears to be a viable option, however existing statutory drive-cycles are unlikely to provide the results sought.

The subsequent research aims to explore typical BTCC racing car data, and locate any potentially suitable drive-cycle concepts.

Achieving this aim will involve fulfilling the following objectives:

Objective 1: Monitor the operating conditions of BTCC racing cars in normal use

Objective 2: Analyse the data collected in 1, for its key characteristics

Objective 3: Collect data on a typical BTCC racing car and showroom equivalent engine performance characteristics to estimate CO_2 emissions

Objective 4: Analyse the results of objectives 2 and 3 as the basis for a drive-cycle / comparative test in the context of the BTCC's planned CO_2 emissions programme

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AN INVESTIGATION INTO WHETHER A BTCC RACING CAR CAN BE SHOWN TO EMIT NO MORE CARBON DIOXIDE THAN ITS SHOWROOM EQUIVALENT

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Abstract

The research aim was to find a method to show a BTCC racing car emitting no more CO_2 than its showroom counterpart. A drive-cycle option was proposed and is investigated. Well-known existing drive-cycles were considered unsuitable in the present context. Thus, in-race operating conditions data for a typical BTCC racing car was collected and analysed. Further data was collected on the specifications and performance of a BTCC racing car and its showroom equivalent. The cars' CO_2 emissions were subsequently estimated. Statistical analysis was carried out on the in-race operating conditions data. The BTCC race data commonly included operating conditions beyond the limitations of the BTCC's dynamometer and the racing car's showroom equivalent.

Under wide-open throttle operation at steady engine speeds between 5500rpm and 6000rpm, the mass of CO_2 emitted per second, by a BTCC racing car, is predicted to be less than that emitted by its showroom equivalent under the same conditions. These engine speeds are uncommon during BTCC races, leaving this comparison open to criticism. Further, such an emissions 'window', may not apply to all BTCC racing cars and their respective showroom equivalents.

At corresponding points across a range of race representative engine speeds, in the upper half of the engines performance range, (5500-8500rpm for the racing car and 3500-6000rpm for the road car), under wide-open throttle operation, steady engine speed emissions tests are predicted to show the

BTCC racing car emitting a similar, or lesser mass of CO_2 per kWh than its showroom equivalent. A series of tests and comparisons under the above conditions is the proposed solution.

Keywords

Emissions Test, Carbon Dioxide, Drive Cycle, Brake Specific Fuel Consumption, Fuel Efficiency

1.0 Introduction

Following UK Government[1] and Automotive Industry[2] initiatives to reduce Carbon Dioxide (CO_2) emissions from passenger cars, the British Touring Car Championship (BTCC) motor-racing series has launched its own emissions reduction programme[3]. The programme aims to generate publicity and promote the championship as being environmentally responsible[3]. BTCC racing cars are modified versions of standard production road cars[4] and a CO_2 emissions limit is proposed for 2009, based upon the latter cars' CO_2 emissions under particular conditions[3].

Thus, the BTCC's Technical Team seeks conditions, which could show current BTCC racing cars emitting no more CO_2 than the road car, conditions which could double as a pre-season homologation test permitting entry to the series[5]. A drive-cycle based emissions test is proposed.

Existing statutory drive-cycles based upon road driving are considered unsuitable in the context of the BTCC's emissions initiative. This article investigates BTCC racing car data as the basis of a bespoke drive-cycle.

Objective 1: Monitor the operating conditions of BTCC racing cars in normal use

Objective 2: Analyse the data collected in 1, for its key characteristics

Objective 3: Collect data on a typical BTCC racing car and showroom equivalent engine performance characteristics to estimate CO_2 emissions

Objective 4: Analyse the results of objectives 2 and 3 as the basis for a drive-cycle / comparative test in the context of the BTCC's planned CO_2 emissions programme

2.0 Literature Review

A drive-cycle has been defined as a chronological series of speed-time data (the typical interval between data points is one second[6]) developed for a particular vehicle type operating in a particular environment, to represent that environment's driving pattern, for the purpose of regulating exhaust gas emissions and fuel consumption[7]. Drive cycles can be simulated repeatedly using Chassis Dynamometers[8], and therefore can also be used to compare the emissions of different vehicles. Thus, in principle, they are suitable for the BTCC's CO_2 emissions comparison and subsequently enforcing an emissions limit.

The basic methodology for drive-cycle development involves[6]:

1. Monitoring the driving conditions using one or more "instrumented" vehicles in normal use
2. Analysing the resulting data to subsequently describe or characterize these conditions
3. Developing one or more cycles, representative of the recorded conditions.

The Modified New European Drive Cycle was developed to reflect typical driving conditions experienced on the public highway in the E.U. using data from European driving[6]. It is used to enforce emissions limits through Type

Approval tests and more importantly here, to provide 'official' fuel consumption figures for cars offered for sale, (including the BTCC racing cars' showroom equivalents).

Fuel consumption is a selling point for road cars[9], thus automobile manufacturers will almost certainly optimise (minimise) the fuel consumption of their products during the driving conditions simulated by the MNEDC. Since road cars destined for the European market typically employ catalytic converters, the mass of CO_2 the car emits is directly related to the mass of fuel used[2]. Thus, such a road car is designed and set-up to minimise its CO_2 emissions during the MNEDC. BTCC racing cars conversely are not designed or set-up with minimising fuel consumption in mind[10] (under any driving conditions). The road cars' total mass of CO_2 emitted during the MNEDC is expected to be significantly less than the total mass emitted by the BTCC racing cars. Therefore the MNEDC is not a suitable drive-cycle for the BTCC emissions programme.

The Federal Test Procedures and Japanese Test Cycles are drive-cycles based on road driving in the United States and Japan respectively[2]. They simulate driving conditions not unlike the MNEDC, albeit that the pattern of the cycles differs[2]. Using either of these cycles (as with the MNEDC) is likely to show the showroom equivalent as emitting significantly less CO_2 than the BTCC racing car. Therefore these cycles are similarly unsuitable for the BTCC emissions programme.

What is needed is a drive-cycle simulating driving conditions where the racing car is fuel efficient in comparison to the road car. BTCC racing cars are optimised to drive around a racetrack in the shortest possible time[10]. It is in such conditions that the racing car could be expected to be at its most fuel (CO_2) efficient. A drive-cycle based upon such driving conditions for which the racing car is optimised might provide the CO_2 emissions results sought.

3.0 Materials & Methods

Objective 1: Collect data on the operating conditions of BTCC racing cars in normal use

Following the standard methodology for drive-cycle development[6], the driving conditions of 'instrumented vehicles' are monitored, with the vehicles in normal use conditions.

The instrumented vehicles in the study were 2008 versions of the 888 / VX Racing Vauxhall Vectras, which are representative of typical BTCC racing cars, complying with the FIA's S2000 regulations in force at the time of writing.

The cars carry mandatory data-loggers, which in the subject cars, was a Pi Research 'Delta' model[11]. This device collects data on the cars' parameters including wheel speed (in mph), engine speed (in rpm) throttle pedal travel, from 0 (closed throttle) to 1 (full throttle) and use of the brakes, (0 or 1: 1 indicating brakes applied, 0 indicating brakes off) all sampled at 0.1s intervals.

The annually calibrated standard "active" anti-lock brake sensors, located in each wheel hub measure wheel speed data, and are triggered 48 times per wheel revolution[11]. Engine speed data is supplied to the data-logger from the Pectel SQ6M Electronic Control Unit[11]. Throttle pedal travel was monitored through a sensor located on the throttle body[12]. Brake use monitors are on/off switches located on the brake pedal / in the brake line[12].

One racing lap should assumed to be much like another in terms of characteristics, thus a single racing lap from a circuit should be representative of all but the start laps at any one circuit. Thus data on the subject cars' operating conditions during a typical single mid-race 'lap' were used. Eight laps were used in the study, representing eight (of the nine) different circuits on the 2008 BTCC calendar. Thus the majority of variation in racing operating conditions experienced by the subject car in a year was included in the study.

Objective 2: Analyse the data collected in objective 1 for its key characteristics

Data Processing

1. From the data the lap times for all eight laps were added together to determine the total time required to simulate the laps.

2. The percentage of samples falling within each of the following classes was calculated:

Closed Throttle – Throttle pedal travel ≥ 0 and ≤ 1%

Part Throttle – Throttle pedal travel > 1% and < 99%

Full Throttle – Throttle pedal travel ≥ 99%

The closed and full throttle classes incorporate an allowance for sensor errors of 1%, applied following initial inspection of the data, in order to avoid the errors significantly affecting the results.

Engine Speed data were limited rounded to integer values. Wheel speed data was converted to kmh^{-1} by multiplying by a factor of 1.61.

The resulting wheel speed and engine speed data could at high resolution be seen to deviate from overall upward trends under acceleration. Significant deviations were believed to attributed to unloading of the wheels on one side of the subject car as kerbing is encountered during cornering.

To gain a clearer idea of the underlying trends i.e. 'road speed' rather than 'wheel speed', a moving average method was used to smooth the data. Corrected data points at time 't', for engine speed and road speed, were determined by finding the mean of the raw data values at t -0.2s, t -0.1s, t, t +0.1s and t +0.2s. This represented a balance between cleaning the data to remove some of the noise and compromising the fidelity of the data.
Data points without two prior or two subsequent data points from which to calculate adjusted road speed were excluded from subsequent analysis.

The rate of acceleration between consecutive resulting data points was subsequently determined using the equation $\Delta v / \Delta t$.

Thus:

Acceleration rate at time t = (speed at time t – speed at time t-0.1s) / 0.1s

The rate of acceleration was limited to two decimal places, further precision deemed unnecessary for the present purposes.

From the data descriptive statistics (maximum, minimum, range, mean, median, mode, standard deviation, variance and skewness) were calculated for:

- Road Speed
- Engine Speed
- Deceleration and
- Acceleration

Objective 3: Collect data on a typical BTCC racing car and showroom equivalent engine performance characteristics to estimate CO_2 emissions

Engine maps detailing the mass of fuel flowing into both engines from which to calculate the corresponding CO_2 emissions (when combined with other information including engine speed and throttle opening) was not available.

A power against engine speed graph was available for a representative FIA S2000 Compliant BTCC racing car engine[16]. An Internet search located the same data for the standard road car's engine[17].

From this data, the two engines' torque curves were subsequently derived, converting power (kW) to torque (Nm) using the formula:

$$\frac{\text{Power (kW)} * 60000}{2\pi * \text{engine speed (rpm)}} = \text{Torque (Nm)}$$

No data was available on the specific Brake Specific Fuel Consumption for the two engines to convert the power output back into fuel consumption. Therefore BSFC estimates were used. These were determined as follows.

For the BTCC racing engine, BSFC values for a 2000cc Opel Competition (racing) engine were used as a starting point[13]. It was assumed that these values were ascertained under the same ambient conditions and using the same fuel as the power data for the BTCC racing engine. The torque curve was derived using the formula above.

With the Opel engine operating at between 2000 and 6000rpm and the BTCC engine operating effectively between 5500 and 8500rpm, the BSFC values for the Opel engine were mapped onto the BTCC engine data as per table 8 below. BSFC at peak torque output for the Opel engine was translated to the point of peak torque output for the BTCC engine. Other Opel BSFC values at 500rpm steps either side of peak torque were mapped on to 500rpm steps on the BTCC engine data. BSFC values between the 500rpm steps were estimated assuming a linear increase/decrease between the established values. BSFC values for the BTCC racing engine from 7750rpm upwards were estimated assuming increasing losses due to increasing friction.

BSFC values for the 2000cc road car engine were derived from typical values taken from a 1900cc engine[14], which were expected to be similar.

To accommodate the turbocharger and intercooler fitted to the road car, adjustments were made to the above BSFC values using factors derived from previous research determining the effects on BSFC values from employing such devices[15]. Conversion factors between the known fractions of engine speed were calculated assuming a linear progression between the known values.

The estimated BSFC values at each engine speed, for each engine was multiplied by the power output at said engine speed to derive the fuel consumption per hour in grams. Dividing this figure by 3600 provided the estimated fuel consumption per second for both engines at the different engine speeds.

The following assumptions were incorporated when comparing the estimated fuel consumption figures of the BTCC racing car and its showroom equivalent.

The BTCC regulations mandate regulation 102 RON fuel[4], which is chemically similar to that sold on retail forecourts[5], therefore both cars are assumed to be using the same fuel, with identical energy density.

It was assumed that the power output data for both engines was comparable (i.e. both engines operating under wide-open throttle operation and under similar ambient conditions).

Objective 4: Analyse the results of objectives 2 and 3 for data in the context of the BTCC's planned CO_2 emissions programme

The results of the aforementioned data collection and processing were analysed to determine whether a comparison method could be derived from them, which fits within the context of the BTCC's Emissions Initiative. More specifically would the comparison:

- Provide results showing the BTCC racing car emitting no more CO_2 than its showroom equivalent.
- Provide the desired results for all racing car and showroom equivalent pairings
- Fit within the limitations of the:
    - Dynamometer
    - Emissions measurement equipment
    - Showroom Equivalent
    - Desired time frame
    - BTCC's Budget for its emissions initiative
    - A pre-season homologation test

- Provide results which would support a publicity campaign, (i.e. they are representative and robust results)

4.0 Results

Objective 1.

The output from the data-logger was presented as a Microsoft Excel spreadsheet for analysis purposes. The data contained 5866 samples and thus cannot be reproduced here in full. An extract from the data is shown below in table 1.

See Table 1

Objective 2.

1.

Table 2 below shows the duration in seconds of a typical BTCC racing lap at eight different circuits in the 2008 calendar.

See Table 2

2.

The distribution of the classes of instantaneous throttle opening showed was as per Table 3 below.

See Table 3

The minimum and maximum engine speeds occurring under wide-open throttle operation were 5933rpm and 8496rpm respectively. The lap data showed the BTCC racing car is always under transient conditions, either accelerating or decelerating.

See Table 4

Objective 3.

BTCC Racing Car Engine Speed at Idle ~2500rpm

Showroom Equivalent Engine Speed at Idle ~800rpm

The power output and torque output data collected for a typical BTCC racing car and its showroom equivalent are shown below in table 5 and 6.

See Table 5

See Table 6

The power output and brake specific fuel consumption at a range of engine speeds, collected for a normally aspirated 1.9L engine from which BSFC estimates for the typical BTCC racing car's showroom equivalent were derived, are shown below in table 7.

See Table 7

The estimated BSFC Values for the BTCC racing car are shown in Table 8 below.

See Table 8

Table 9 below, shows the underlying adjustment factors used to convert the BSFC figures for the naturally aspirated 1.9L engine into those for the showroom equivalent equipped with a turbo-charger and intercooler.

See Table 9

The specific conversion factors to convert the naturally aspirated 1.9L engine BSFC figures to those for a turbo-charged and inter-cooler equipped engine, and the resulting BSFC estimates for the showroom equivalent are shown in Table 10 below.

See Table 10

The estimated fuel consumption ($g \cdot s^{-1}$) per second figures at a range of engine speeds are shown below in table 11.

See Table 11

The estimated fuel consumption per second ($g \cdot s^{-1}$) for the BTCC racing car's showroom equivalent are shown below in Table 12.

See Table 12

Figure 1 below graphically represents the estimated fuel consumption per second ($g \cdot s^{-1}$) of both cars at across a range of engine speeds.

See Figure 1

5.0 Discussion

Objective 4: Analyse the results of objectives 2 and 3 as the basis for a drive-cycle / comparative test in the context of the BTCC's planned CO_2 emissions programme

In the following analysis of the results, for the sake of brevity, only key criteria for each comparison method will be discussed, rather than considering them all exhaustively.

Developing drive-cycles based on road driving, typically involves condensing many hours of heterogeneous operating conditions into something approximating a 1200 second simulation[2]. BTCC race operating conditions, differ from road driving operating conditions, in that they typically involve twenty or so laps, which range from approximately 49 to 88 seconds in duration. Excluding the start laps, there is relatively little variation between typical laps at any one circuit, i.e. they are homogeneous in terms of duration and speed and rate of acceleration or deceleration at any point around the circuit. Therefore simulating one lap in a drive-cycle is essentially simulating the other 60 or so laps at the same circuit.

There are variations observed in the operating conditions at different circuits. However, the duration of the laps means all of these variations could be accounted for in a period of approximately 587 seconds. Allowing for time to warm the engine, ‘accelerating’ up to speed and speed changes between laps slowing to ‘rest’ and the missing Silverstone lap (not included due to time constraints), the entire 2008 season’s racing could, in theory be replicated in approximately 15mins, well within the timeframe for a typical drive-cycle.

In practice however such a drive-cycle is less feasible when considering the laps’ statistics. The deceleration statistics should be treated with caution, since some of the samples showing the highest rates of deceleration (peaking at -31.88ms^{-2}) may reflect changes in wheel-speed (instances where the wheels almost stop rotating) rather than rapid changes in road speed. Nevertheless, a mean and median deceleration rate of 6.04ms^{-2} and 5.25ms^{-2} indicates that a significant proportion of the samples lie beyond the BTCC dynamometer’s 4ms^{-2} braking limit[18]. In other words, not all braking can be replicated by the BTCC’s ‘performance’ dynamometer.

Limiting drive-cycle braking to a maximum of 4ms^{-2} and extending the braking periods would accommodate this obstacle. However, when braking, the cars typically operate under closed throttle operating conditions, using it is assumed, the same mass of fuel as engine-idle. Engine speeds at idle are typically approximately 2500rpm[17] and ~800rpm for a typical BTCC racing car and a showroom model respectively. The higher idling engine speed of the racing car is indicative of a greater mass of fuel entering the engine during closed throttle braking. Since CO_2 emissions are a direct index of the mass of fuel used in the study vehicles[2], the higher engine idle speed indicates the BTCC racing car emits a greater mass of CO_2 under braking than the road car. Extending the duration of (closed throttle) braking, therefore serves to show BTCC racing cars emitting more rather than less CO_2 than its showroom equivalent.

Unlike race deceleration, the BTCC dynamometer is capable of simulating the majority of acceleration samples (all bar 7% fall within the $4ms^{-2}$ limit). The road car is unlikely to be so accommodating. Of the acceleration data, 76% of samples are at full throttle operation at engine speeds between 5933 and 8496rpm. Under these conditions, the racing engine is delivering a power output greater than the showroom equivalent's peak power output. Further, that power is delivered to a lower mass (BTCC racing car: ~1200kg including driver, road car: ~1456kg plus driver for the road car). Since force / mass = acceleration, under full throttle operation, the racing cars rate of acceleration will be greater than the road car is capable of. Thus the road car cannot be tested using a drive-cycle simulating the full-throttle operating conditions of a BTCC race, which accounts for 63% of all samples.

While the road car cannot replicate the transient conditions experienced by a BTCC racing car during a race, it can replicate most of the speeds[9]. The instantaneous fuel consumption estimates are just that, estimates, and the results need to be treated with caution. That said, the estimates suggest that between ~5500rpm and ~6000rpm the road car (nearing its maximum rpm) is using more fuel per second than the racing car, (which is not near its maximum engine speed). The difference between the fuel consumption is significant enough that allowing for errors in the estimates, the racing car might still use no more fuel than the road car at this engine speed. Thus the racing car would emit no greater mass of CO_2 emitted per second, than the road car.

An emissions test (rather than a drive-cycle), where the cars operate under wide-open throttle conditions, at steady engine speeds between 5500rpm and 6000rpm is expected show the racing car emitting a lower mass of CO_2 per second, than its showroom equivalent. However, such a drive-cycle has potential weaknesses.

First, while the BTCC racing car and showroom equivalent in the study is expected to have a small window of engine performance, where the racing car emits no greater mass of CO_2 per second, than its showroom equivalent, the applicability of such a test across other BTCC cars on the grid is doubtful. While the BTCC racing cars may be assumed to be somewhat homogeneous in their performance characteristics as a result of the strict regulations, no such homogeneity is anticipated amongst the showroom equivalents. Thus, no such window may exist with other BTCC racing car / showroom equivalent pairings.

Secondly, while technically the above comparison would be correct and favour the racing car, the in-race data collected, shows the sample BTCC racing car spending only 2.6% of the eight laps, operating at such engine speeds. Further, this range of engine speeds is more than 3 standard deviations from the mean engine speed. Therefore, criticism could be levelled at the BTCC, for formulating a test, which is unrepresentative of typical BTCC racing car emissions.

With a mean in-race engine speed of ~7500rpm and a standard deviation of 460rpm, tests comparing the BTCC engine operating between approximately 6600rpm and 8400rpm would be more representative. At such engine speeds, the mass of CO_2 emitted per second by the racing car is greater than the road car is predicted to be capable of producing at any engine speed. This is due to the higher engine speeds attainable by the racing engine and the consequently higher power output. A comparison on this basis would therefore not support the planned publicity.

The BSFC estimates for the cars however, suggest that a solution to the BTCC's problem lies there. For explanatory purposes an engine's operating range extends from minimum engine speed, (idle), denoted as 0.0 engine speed, to the maximum speed attainable at the rev limiter, (denoted 1.0). Idle (0.0) for the BTCC car is 2500rpm[10] and maximum engine speed (1.0) is 8500rpm. The in-race data collected shows that 99% of the eight laps, and 100% of the samples characterised by full-throttle operation, are characterised by engine speeds above 0.5 (i.e. 5500rpm).

In the road car 0.0 is ~800 to 1000rpm and 1.0 engine speed is 6000rpm, meaning 0.5 engine speed is ~3500rpm. Therefore racing in the road car would theoretically occur with the engine running at between 3500rpm and 6000rpm.

The BSFC estimates for the typical BTCC racing car and showroom equivalent are ~259g·kWh^{-1} and 261g·kWh^{-1} at 0.5 engine speed and ~280g·kWh^{-1} and 320g·kWh^{-1} at 1.0 engine speed respectively. Where a showroom equivalent is naturally aspirated, the BSFC estimates are 260g·kWh^{-1} at 0.5 and 350g·kWh^{-1} at 1.0. At these points and others in between, (0.6, 0.7, 0.8 engine speed), the racing car is expected to use a similar or lower mass of fuel to generate a kWh of output, than its showroom equivalent running at corresponding engine speeds.

Since these estimates are taken from a range of engine speeds, which accurately represent engine speeds experienced during BTCC races, a comparison of emissions on this basis could be considered more robust than the earlier method which operates between 5500rpm and 6000rpm, a little used range of engine speeds. Thus it is expected to be more resilient to criticism than the earlier method.

It is assumed the typical BTCC racing car studied, is representative of most other BTCC racing cars, (the strictly enforced regulations should ensure similarity between engines and cars). Therefore, the BSFC estimates can theoretically be applied to all other BTCC racing cars. Further, since BSFC figures are often applicable to a range of similarly configured internal combustion engines[19], the showroom equivalent BSFC estimates should be transferable to the showroom equivalents of other BTCC racing cars. Thus such a method of comparison is in theory, applicable across the grid.

The BSFC figures are a measure of relative engine efficiency. Racing itself may not be an efficient way of travelling, due to the greater energy losses (to heat in through the brakes and overcoming higher aerodynamic resistance) compared to a less aggressive style of driving, however, where it is done, a BTCC racing car is estimated to be more fuel-efficient (uses a lower mass of fuel to generate a kWh) than it's showroom equivalent. Since the mass of fuel used by an internal combustion engine (fitted with a catalytic converter) is an index of the mass of CO_2 it produces, it is estimated that a BTCC racing car emits a lesser mass of CO_2 per kWh, at typical (full-throttle) racing engine speeds than its showroom equivalent operating at corresponding engine speeds (0.5, 0.6, 0.7 etc.).

A series of emissions tests, which involves measuring the mass of CO_2 per kWh produced across a range of 'steady' engine speeds between 0.5 and 1.0 engine speed, under wide-open throttle operation would:

- Be representative of BTCC in-race operating conditions
- Be resilient to the criticism of being unrepresentative of in-race emissions
- Be a demonstration of higher engine efficiency, on the part of the racing car, which has connotations of resource efficiency and environmental responsibility

- Be feasible, since it is within the limitations of the complimentary dynamometer and CO_2 measurement device currently used by the BTCC and all showroom equivalents
- Be feasible within the BTCC budget as a result
- Be feasible within the BTCC’s preferred time frame for publicity activities
- Be feasible as a pre-season homologation test
- Prove that under a range of operating conditions, a BTCC racing car can emit no more CO_2, than its showroom equivalent.

6.0 Conclusions

Objective 1.

In-race data was collected during 2008 from the data-logger fitted to a typical 2008 FIA S2000 Regulation compliant BTCC racing car, for eight different circuits on the 2008 calendar.

Objective 2.

The data was analysed for the duration of laps and descriptive statistics were determined for in race road speed, engine speed, rate of deceleration and rate of acceleration.

Objective 3.

Data on power output (kW) at a range of engine speeds as well as engine idle speeds, mass and brake specific fuel consumption were collected for a typical 2008 FIA S2000 compliant BTCC racing car and its showroom equivalent.

Objective 4.

A dynamic drive-cycle simulating BTCC race operating conditions (acceleration and braking) is unsuitable concept in the context of BTCC's emissions programme, due to the BTCC's dynamometer's and the showroom equivalent's limitations.

Estimates suggest that under wide-open throttle operation between 5500rpm and 6000rpm, the study BTCC racing car would emit a similar or lesser mass of CO_2 per second than its showroom equivalent. An emissions test based on such conditions would therefore show this BTCC racing car emitting no more CO_2 than its showroom equivalent. Such a window may not exist between other BTCC racing cars and their showroom equivalents. Even if it does, it is likely to exist at similar engine speeds, which are unrepresentative of typical racing conditions (and therefore emissions), leaving such a comparison open to criticism. This is undesirable when the comparison aims to generate positive environmental publicity for the series and the concept is, therefore, unsuitable for the emissions programme.

Wide-open throttle operation, at corresponding steady engine speeds in the upper half of each engines performance range (5500rpm to 8500rpm for the racing car, and 3000rpm to 6000rpm for the road car) is expected to show the racing car emitting a similar or lower mass of CO_2 per kWh than its showroom equivalent (irrespective of the latter's method of aspiration). A comparison based on a range of such conditions, would be resilient to criticism in the public arena, since operating conditions and therefore resulting emissions, are representative of those experienced in-race by a BTCC racing car. An emissions test, based on such operating conditions is feasible within the constraints of the BTCC's emissions programme and could operate as a pre-season homologation test for the series. As such this is the concept, which is recommended for further investigation as a platform to prove that a BTCC racing car, can under a range of conditions, emit no more CO_2 than its showroom equivalent.

7.0 Research Limitations

It should be noted that the in-race data analysed above, was from one BTCC racing car, in one lap from eight different circuits and there may be some variation in the operating conditions experienced by other cars driven by other drivers. However, given the detailed regulations governing BTCC racing cars[4,20,21] (and their strict enforcement), to ensure the racing remains ‘close’ and therefore exciting[22], the variations between cars and driving styles are not expected to be significant enough to affect the results of the study.

The BSFC figures and adjustment factors used in the study were estimates based on previous research, and should not be treated as definite. However they are believed to be sound enough to warrant further investigation to determine the precise figures.

8.0 Recommendations for Further Research

It is recommended that the brake specific fuel consumption figures for a BTCC racing car and its showroom equivalent be determined and compared, with the former operating at a range of engine speeds between 6600rpm and 8500rpm and the latter operating between 3500rpm and 6000rpm.

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Tables

Table 1. Extract of 'In Race' Data in Microsoft Excel Spreadsheet Form

Time	Brake TOCA	RPM	Throttle TOCA	Wheel Speed 1[mph]
138.4	0	7786.000195	1	104.390369
138.5	0	7882.000085	1	105.136015
138.6	0	7932.000055	1	105.943796
138.7	0	7991.999635	1	106.440893
138.8	0	7979.00005	1	106.689442
138.9	0	8062.999715	1	107.248676
139.0	0	8120.999755	1	107.870048

Table 2. Duration of Typical Laps

Circuit	Lap Duration (s)
Brands Hatch	49.4
Croft	85.7
Donington Park	72.7
Knockhill	53.9
Oulton Park	88.2
Rockingham	85.0
Snetterton	71.8
Thruxton	79.3
Total	586.6s (9m 46.6s)

Table 3. Distribution of Samples by Throttle Opening

Class	Throttle pedal travel range	Frequency	% of total (n=5866)
Closed Throttle	≥ 0 & < 0.01	1013	17.3
Part throttle	≥ 0.01 & < 0.99	1158	19.7
Full Throttle	≥ 0.99	3695	63.0

Table 4. BTCC Race Data Descriptive Statistics

	Road Speed (kmh^{-1})	Engine Speed (rpm)	Deceleration (ms^{-2})	Acceleration (ms^{-2})
Mean	149.4	7496.3	-6.04	2.21
Median	150.7	7586.3	-5.25	2.11
Mode	n/a	n/a	-9.39	2.44
Minimum	52.1	4980.3	-0.02	0.005
Maximum	234.8	8345.3	-31.88	13.45
Range	182.7	3365.0	-31.85	13.45
Standard Deviation	35.9	460.6	4.96	1.25
Sample Variance	1287.6	212194.8	24.67	1.553
Skewness	-0.054	-1.05	0.96	1.54
Standard Error	0.47	6.03	0.125	0.019
n =	5834	5834	1564	4251

Table 5. Power and Torque Outputs for a Typical 2008 BTCC Racing Car[16]

Engine Speed (*rpm*)	Power (kW)	Torque (Nm)
5500	119	207.0
5750	114	189.5
6000	121	192.1
6250	147	224.9
6500	161	236.8
6750	174	246.8
7000	180	246.0
7250	184	242.4
7500	191	242.7
7750	195	240.3
8000	202	240.7
8250	206	238.5
8500	203	228.2

Table 6. Power and Torque Outputs for the Showroom Equivalent[17]

Engine Speed (rpm)	Power Output (kW)	Torque Output (Nm)
1001	14.5	138.3
1603	31.7	188.8
1803	41.4	219.3
2005	50	238.1
2504	67.7	258.2
2705	73	257.7
3005	80.7	256.4
3608	96.4	255.1
3810	102	255.7
4009	106.7	254.2
4513	113.5	240.2
5014	116.9	222.6
5314	118.9	213.7
5500	120.9	209.9
5750	119.9	199.1
6000	116.1	184.8

Table 7. Data for a 2000cc Opel Racing Engine[13]

Engine Speed (rpm)	Power output (kW)	Torque output (Nm)	BSFC
2000	34	162.34	258
2500	45	171.89	255
3000	60	190.99	252
3500	75	204.63	252
4000	90	214.86	255
4500	110	233.43	259
5000	125	238.73	261
5500	148	256.96	263
6000	150	238.73	265
6500	140	205.68	268

Table 8. BTCC Racing Car Data and Estimated BSFC Values

Engine Speed (rpm)	Power (kW)	BSFC est.
5500	119.23	259
5750	114.08	265
6000	120.70	260
6250	147.20	261
6500	161.18	262
6750	174.43	263
7000	180.32	265
7250	184.00	267
7500	190.62	268
7750	195.04	270
8000	201.66	273
8250	206.08	276
8500	203.14	280

Table 9. BSFC Adjustment Factors Converting Naturally Aspirated Engines to Turbocharged and Inter-cooled Equivalents[15]

Relative Engine Speed	Adjustment factor
min	0.876
1/4 rpm	0.985
1/2 rpm	0.969
3/4 rpm	0.95
max	0.914

Table 10. Estimated BSFC Values for the Turbocharger and Inter-cooler Equipped Showroom Equivalent

Road Car Engine Speed	1900cc Engine BSFC Values[13]	Turbo + Intercooler Conversion Factor[15]	Estimated BSFC
1001	260	0.876	228
1603	260	0.928	241
1803	260	0.946	246
2005	260	0.963	251
2504	260	0.982	255
2705	260	0.979	255
3005	265	0.975	259
3608	270	0.968	261
3810	275	0.964	265
4009	280	0.961	269
4513	300	0.953	286
5014	320	0.942	302
5314	330	0.933	308
5500	340	0.928	316
5750	345	0.921	318
6000	350	0.913	320

Table 11. BTCC Racing Car Estimated Fuel Consumption per second

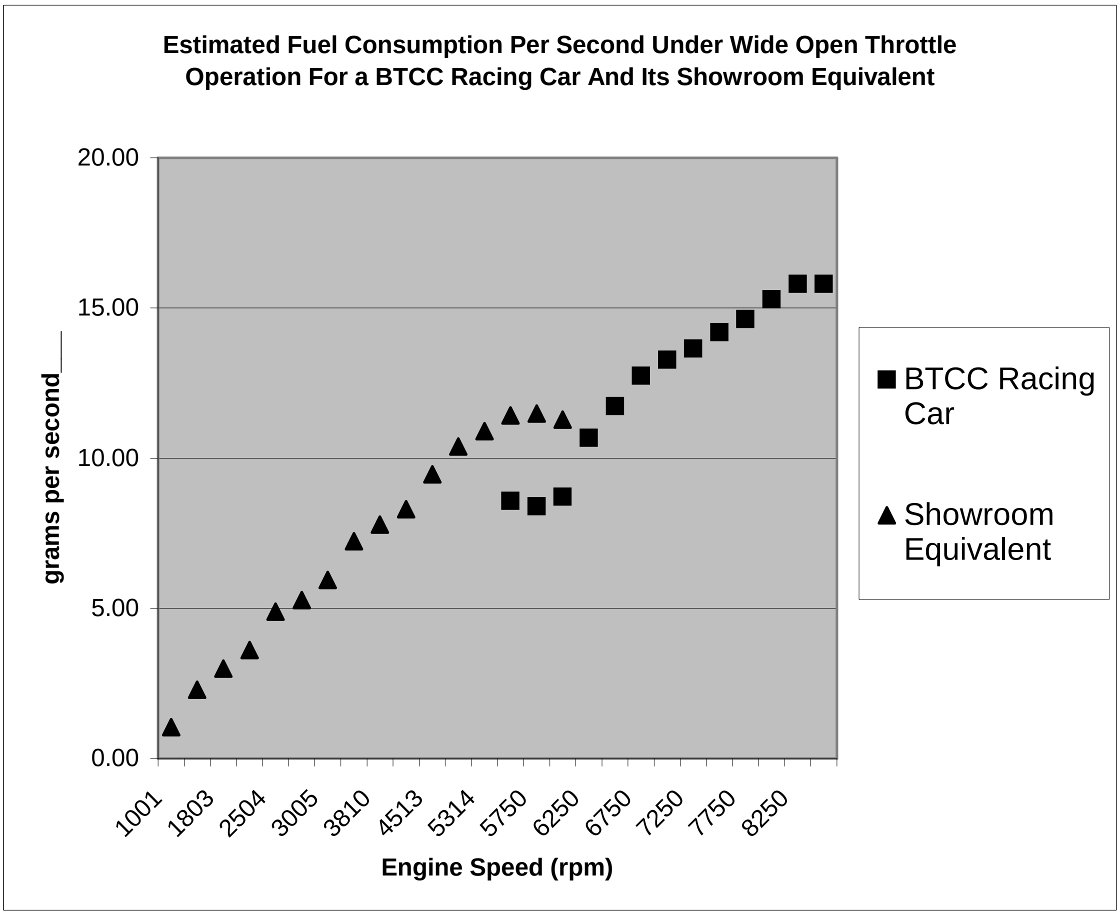
Engine Speed (rpm)	Power Output (kW)	Estimated BSFC	Estimated fuel consumption gs^{-1}
5500	119	259	8.58
5750	114	265	8.40
6000	121	260	8.72
6250	147	261	10.67
6500	161	262	11.73
6750	174	263	12.74
7000	180	265	13.27
7250	184	267	13.65
7500	191	268	14.19
7750	195	270	14.63
8000	202	273	15.29
8250	206	276	15.80
8500	203	280	15.80

Table 12. Showroom Equivalent Estimated Fuel Consumption per second

Engine Speed (rpm)	Power Output (kW)	Estimated BSFC ($g \cdot kWh^{-1}$)	Estimated fuel consumption ($g \cdot s^{-1}$)
1001	14.5	228	1.05
1603	31.7	241	2.29
1803	41.4	246	2.99
2005	50	251	3.61
2504	67.7	255	4.89
2705	73	255	5.27
3005	80.7	259	5.94
3608	96.4	261	7.23
3810	102	265	7.79
4009	106.7	269	8.30
4513	113.5	286	9.46
5014	116.9	302	10.39
5314	118.9	308	10.90
5500	120.9	316	11.42
5750	119.9	318	11.49
6000	116.1	320	11.29

Figures

Figure 1. Estimated Fuel Consumption Per Second Under Wide Open Throttle Operation For a BTCC Racing Car And Its Showroom Equivalent



Appendix

Notation

Δ	Delta (change in)
π	Pi
BSFC	Brake Specific Fuel Consumption
BTCC	British Touring Car Championship
CO_2	Carbon Dioxide
E.U.	European Union
FIA	Federation Internationale d'Automobiles
g	gram
g·kwh-1	grams per kilowatt hour
kg	kilograms
kmh^{-1}	kilometres per hour
kW	kilowatts
kWh	kilowatt hour
MNEDC	Modified New European Drive Cycle
mph	miles per hour
ms^{-1}	metres per second
ms^{-2}	metres per second per second
Nm	Newton metre
RON	Research Octane Number
rpm	Revolutions per minute
s	second

End of Paper

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