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Measurement of Formula One Car Drag Forces on the Test Track.

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ABSTRACT

Coastdown testing is a proven method for determining the drag coefficients for road cars whilst the vehicle is in its normal operating environment. An accurate method of achieving this has been successfully developed at Loughborough University. This paper describes the adaptation and application of these techniques to the special case of a contemporary Formula One racing car. The work was undertaken in conjunction with the Benetton Formula One racing team.

The paper outlines the development and application of a suitable mathematical model for this particular type of vehicle. The model includes the aerodynamic, tyre, drivetrain and the un-driven wheel drags and accounts for the change in aerodynamic drag due to ambient wind and changes in vehicle ride height during the coastdown. The test and analysis methods are described.

The results from a series of coastdown tests conducted at a current Grand Prix circuit are presented and compared to the results from tyre rig and wind tunnel measurements.

INTRODUCTION

Accurate measurement of the resistance to motion of a vehicle in its normal operating environment is of vital importance to the production of data for vehicle perform-

ance assessment and for the validation of wind tunnel test work. The coastdown method has been used, over a number of years, in an attempt to determine the tyre and aerodynamic drag coefficients for normal road cars from track data. Such tests have met with varying degrees of success because of the wide variability to be expected in environmental testing. A sophisticated method developed at Loughborough University^{1,3}, for use on conventional road cars, has been proven to yield accurate values of the coefficients. This paper details a study into the application of coastdown to the rather specific application of a Formula One type racing car.

The principle of the coastdown test is simple. The test vehicle is driven up to the maximum speed of interest on a straight road, shifted to neutral and allowed to freely decelerate. The deceleration is proportional to the total drag force. In practical testing the vehicle speed is recorded as a function of time and analysed to extract the drag coefficients. To ensure that the results are both accurate and repeatable it is important to take account of all sources of drag and the influence of ambient conditions, the most important of which is the wind input. A feature of this method is the use of an on board anemometer to continuously measure wind speed.

There are of course major differences between standard road cars and Formula One cars. The latter generate very high normal load forces, via the use of body shape and wing sections, have very high aerodynamic

drag coefficients, run at very low ground clearances and use slick treaded tyres. These aspects have major implications on the use of the coastdown method to determine drag coefficients. The main problem is in the formulation of a suitable mathematical model to describe the drag forces acting on the vehicle during coastdown. If the representation used is not a realistic one then the various sources of drag cannot be properly separated. During development of the model a coastdown simulation program was used to assess the importance of each component of the drag function, enabling assessment of the influence of modelling errors and in the specification of the test procedure.

Although not specifically required for coastdown testing, data from routine wind tunnel tests has been used during the adaptation of the technique to the F1 car. The data is used to assess the importance of ride height changes, yaw angle effects, and for the calibration of the on-board anemometer. In addition it also provides a basis for comparison between track and tunnel. The wind tunnel installation used provides a speed of 40m/s, has a tensioned high suction moving belt and cooled platen. The 40 per cent scale model gave a blockage of 4 per cent.

To protect the confidential nature of the data obtained from this work, much of the graphical data is shown without axis scales, however the values of all the drag coefficients reported are the actual values determined from the tests.

MATHEMATICAL MODEL

The mathematical model used to describe the car's longitudinal motion during coastdown is based on that used for a conventional car.¹ The equation of motion for the vehicle travelling in a straight line is a straight forward application of Newton's second law.

$$F_T = F_D(v) + M_e \frac{dv}{dt} + M_g \sin a$$

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Tractive Effort	Resistive Force	Inertial Force	Gravitational Force
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During the coastdown test the tractive effort is zero. The resistive force plus gravitational force is therefore proportional to the acceleration, and if the track gradient is known then the total drag force can be determined. The inertia (M_e) includes an allowance for any rotating components as well as the basic vehicle mass.

$$\frac{dv}{dt} = \frac{-(F_D(v) + M_g \sin a)}{M_e}$$

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Defining the form of the resistive force function presents one of the main obstacles in analysing the coast-

down data. If it is not a realistic model of the real world then results will be accordingly biased and the components of drag will not be correctly separated.

AERODYNAMIC DRAG is the product of the free stream dynamic pressure, the aerodynamic drag coefficient and a reference area. In the presence of ambient wind the coefficient may be modified with yaw angle and the drag depends on the total airspeed. In addition in the case of the F1 car with very low ground clearance the drag coefficient is also sensitive to front and rear ride height. The treatment of the ambient wind effects is covered in detail by Passmore¹. For a conventional car the variation of C_d with yaw angle is modelled reasonably well with a parabolic form^{1,2}. Only very limited data was available for the F1 car tested here, but in conjunction with the simulation software it was concluded that the airspeed should be recorded throughout the coastdown test and that provided the mean airspeed was low (less than 2m/s) the yaw meter could be dispensed with (The effect is included in EQ (3) for completeness). The variation of C_d with front and rear ride height depends on the pitch and heave sensitivity, and was assessed using wind tunnel data. These show a total variation in C_d of approximately 1.5 per cent for the vehicle attitude changes experienced during coastdown. Simulation tests showed that neglecting this effect could produce errors of the order of 10 per cent in A_d , 20 per cent in B_d and 1 per cent in the converged value of C_d . It is therefore included in the model as the function $f(\mathbf{d}_f, \mathbf{d}_r)$, During the analysis the correction is interpolated from the wind tunnel data. The complete aerodynamic model is shown in EQ (3).

$$\text{Aerodynamic drag} = \frac{1}{2} \rho A v_r^2 [C_{d_0} + K_d Y^2 + f(\mathbf{d}_f, \mathbf{d}_r)] \quad 3$$

MECHANICAL LOSSES are a combination of the tyre losses and losses from the drive train and un-driven wheels. The tyre losses are speed and load dependant and are normally modelled in the form shown in EQ (4). Where the normal load is simply the vehicle weight (Mg).

$$\text{Tyre loss} = (\text{Normal load})(A_d + B_d v) \quad 4$$

It is usual to ignore the effect of aerodynamic lift on the tyre normal load as it represents only 1 or 2 per cent of the vehicle weight. This is clearly not the case for an F1 car and it is therefore included in EQ (5). As the car generates down-force the lift coefficient is negative and therefore has the effect of increasing the weight.

$$\text{Tyre loss} = (Mg - \frac{1}{2} \rho A C_l v_r^2)(A_d + B_d v) \quad 5$$

EQ (5) shows that including the aerodynamic lift introduces a v_r^2 term to the tyre losses. During the analysis of the coastdown data this cannot be separated

from the v_r^2 term in the aerodynamic drag (EQ 3), as they are perfectly correlated. The problem is eliminated if the lift force is known throughout the test. If wind tunnel data is used to generate the force then it should be remembered that the lift coefficient is also dependent on yaw angle and vehicle attitude. In this work the vehicle was equipped with strain gauge transducers on the suspension pushrods so it was possible to continuously measure the normal load force, allowing C_l to be quantified throughout the test.

In addition to the dependence on load and speed the rolling resistance is also influenced by temperature and inflation pressure. Assuming that temperature correction data is obtained with a fixed mass of air in the tyre, the two effects can be accounted for in a single correction factor. In these tests the correction factor³ is based on ambient temperature using the coefficient K_T equal to 0.011 /K, this coefficient is for conventional road car tyres since no alternative was available.

$$\text{Rolling loss} = (Mg - \frac{1}{2} rAC_l v_r^2)(A_d + B_d v)[1 + K_T(T_o - T_s)]$$

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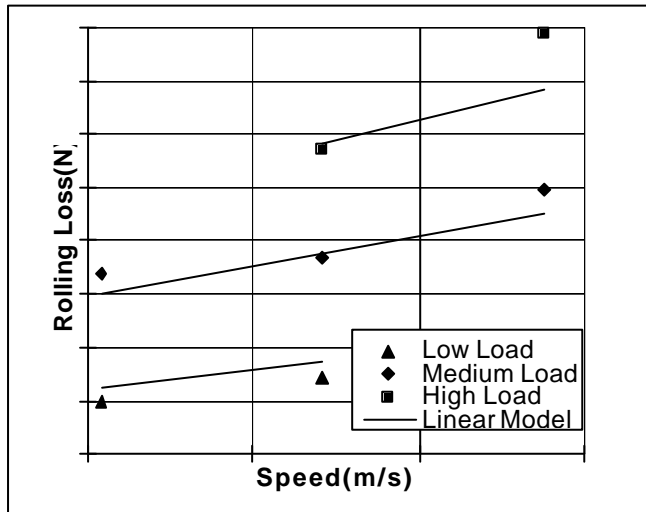


Figure 1 Tyre dynamometer data compared with tyre model.

As in the case of the wind tunnel tests tyre rig data is not essential for the coastdown analysis. However it has been obtained in independent tests by the tyre manufacturers and is used here in the validation of the tyre loss component of the mathematical model. The rig data is shown in Figure 1 with the proposed mathematical tyre loss model superimposed for comparison. All tyre dynamometer rig tests were undertaken at room temperature, with tyre pressures front and rear of 22 and 20 PSI respectively, with wheel cambers -2.5° front and 0° rear.

At the highest speed and load the tyre drag calculated using the Linear Model is approximately 50 N lower than that determined from tyre dynamometer rig testing.

Although this represents less than 1 per cent of the total drag at this speed it could be a source of error in the coastdown analysis because of the close relationship between the coefficients. However the data from the tyre manufacturers is for normal loads significantly higher than were experienced with the vehicle set-up used in the coastdown tests, which are much closer to the medium to low load range. This was due to mid season rule changes limiting the normal load forces generated by the cars. The fit to the data in the medium load region is good, with an rms. error of the order of 10N.

Mechanical losses in addition to the tyres arise from the transmission, which though in neutral gives rise to drag from oil churning, gear meshing, bearings, brake drag and the un-driven wheels. Brake drag may be effectively eliminated in the test procedure, but the remainder must be measured in separate laboratory experiments. The term $F_M(v)$ accounts for the transmission and un-driven wheel losses as a function of speed.

TOTAL DRAG is the sum of the forces discussed. The complete drag function is shown in EQ (7). The object of the coastdown analysis is to determine the unknown coefficients (A_d, B_d, C_d) in the equation.

$$F_D(v) = (Mg - \frac{1}{2} rAC_l v_r^2)(A_d + B_d v)[1 + K_T(T_o - T_s)] + \frac{1}{2} rAv_r^2[C_{d_0} + K_d y^2 + f(d_f, d_r)] + F_M(v)$$

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INSTRUMENTATION

Coastdown data was acquired at 50 Hz, using the on-board data logger, in conjunction with largely standard instrumentation. At the start of each track test session the logger was initialised and data recorded throughout the test. On return to the pits the data is downloaded to a P.C. and the coastdown data is extracted from the remainder of the data. The following principle measurements are made.

Vehicle speed was determined via a 48 tooth disk and an inductive pickup mounted in the hub.

Lift force at each wheel was calculated from the output of strain gauges installed in the suspension pushrods.

Airspeed was measured using a pitot probe in line with the vehicle's direction of travel, located at the front of the car, close to the front suspension mounting.

Ride height was measured at each of the four wheels and averaged over each axle to produce front and rear ride height values. The ride height at each wheel is calculated from measurements of damper deflection without allowance for tyre deflection. However for the purposes of coastdown testing, where we are concerned with ride height changes, this is felt to be adequate.

In addition to the main measurements the ambient pressure, temperature, vehicle mass and mean track side ambient wind data were recorded.

TEST METHOD

The test was designed to be as simple as possible to perform so that it could be undertaken during routine track testing on existing Grand Prix circuits.

Before beginning the coastdown tests, the car was weighed complete with driver, the ride heights, wing settings, tyre pressures, wheel camber / caster and toe settings were recorded, and the data logger initialised. Prior to testing the tyres were heated in the tyre blankets, as is usual practice, to a temperature between 80 and 90°C to minimise the warm up time. An additional two laps of the circuit is then considered sufficient for the tyres to stabilise.

Ideally each coastdown should be conducted from a start speed of 80 m/s down to a minimum of 20 m/s. The preferred procedure is to perform the tests in pairs conducted in opposite directions on the track. The paired data can then be used to calibrate the on-board anemometer,¹ necessary due to the proximity of the device to the vehicle. However in this case it was only possible to test in a single direction, so the anemometer calibration was obtained during tunnel tests. The car was accelerated up to approximately 80m/s at the start of the main straight, allowed to stabilise and the clutch disengaged to allow the vehicle to coastdown. In the event of interference from another vehicle, e.g. passing whilst it is coasting down then the test is considered void.

The test should be repeated a number of times to improve the accuracy of the extracted coefficients. In the tests reported here time constraints limited the total number to four.

COASTDOWN ANALYSIS

The coefficients in the coastdown equation described are determined by fitting the mathematical model to the measured speed data using an optimisation routine to minimise the *cost* function $F(\mathbf{x})$. Where \mathbf{x} is a vector representing the estimate of the coefficients, and $F(\mathbf{x})$ is the sum of errors squared. The analysis is performed by integrating the coastdown equation, using \mathbf{x} to generate a simulated coastdown with the same start speed and time increments as the measured data. By comparing the simulated data with the measured data the *cost* can be evaluated. The measured airspeed and lift force along with the results from the laboratory driveline tests are used as input during the integration.

$$F(\mathbf{x}) = \sum_{i=1}^m [f_i(\mathbf{x})]^2 = \sum_{i=1}^m [v_{m_i} - v_i(\mathbf{x})]^2 \quad 8$$

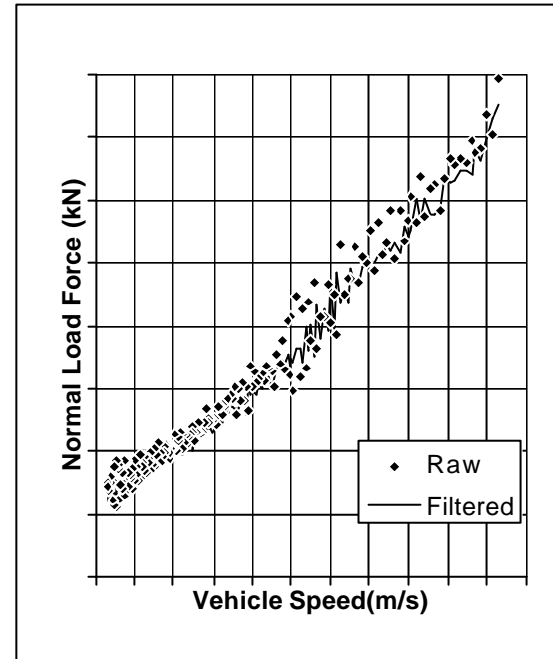
By varying the values of the coefficients in the vector \mathbf{x} the optimisation routine converges to a minimum of the *cost* to give the best estimate of the coefficients. This method of extracting the coefficients directly from

the measured speed data avoids the need to differentiate measured data.

A facility within the coastdown analysis outlined by Passmore^{1,3} allows one or more of the coefficients to be constrained to a fixed value. This was shown to have advantages in comparative testing. Although not directly used in this work a similar technique has been used here to further assess the influence of the tyre model described earlier. The two tyre coefficients (A_d and B_d) are removed from the analysis and replaced with an interpolation routine which directly accesses the tyre rig data (Figure 1), to generate the tyre loss for the known load and speed. This allows the effect of the tyre model on the converged value of C_d to be determined.

Prior to the optimisation analysis the normal load data is pre-processed to remove inputs due to road surface irregularities. With a suspension natural frequency of approximately 6Hz a low pass filter cut off frequency of 4Hz was selected. A comparison of the raw and filtered data is shown in Figure 2.

Figure 2. Raw and filtered normal load.



DRIVELINE AND UN-DRIVEN WHEEL LOSS RESULTS.

The losses in the drivetrain during coastdown must be measured during laboratory tests prior to reduction of the principal track coastdown data as they cannot be separated within the analysis. With the vehicle raised from the ground and the suspension supported so that it is in the normal track configuration a coastdown on the drivetrain alone can be performed. The drivetrain was driven up to an appropriate vehicle speed using the engine and once at operating temperature de-clutched, the gearbox set in neutral, and the drivetrain allowed to coastdown. During the coasting phase the wheel speed

was recorded as a function of time. Using values for the drivetrain inertia the losses can be calculated. Due to problems with the test set-up and time constraints the maximum speed was limited to only 23 m/s, and since the main coastdown tests were over a much higher speed range, the model proposed is arbitrary.

The raw data is fitted with a linear function to reduce the possibility of large errors when the data is extrapolated to generate the drivetrain loss at the higher vehicle speeds encountered during coastdown ($loss = A_t + B_tv$). After repeating the test a number of times the coefficients were averaged to yield drivetrain loss coefficients. The un-driven wheel losses were measured in a similar fashion, with the power to drive the wheel up to a suitable speed being provided with an electric motor. The un-driven wheel losses are shown for different hub temperatures in Figure 3.

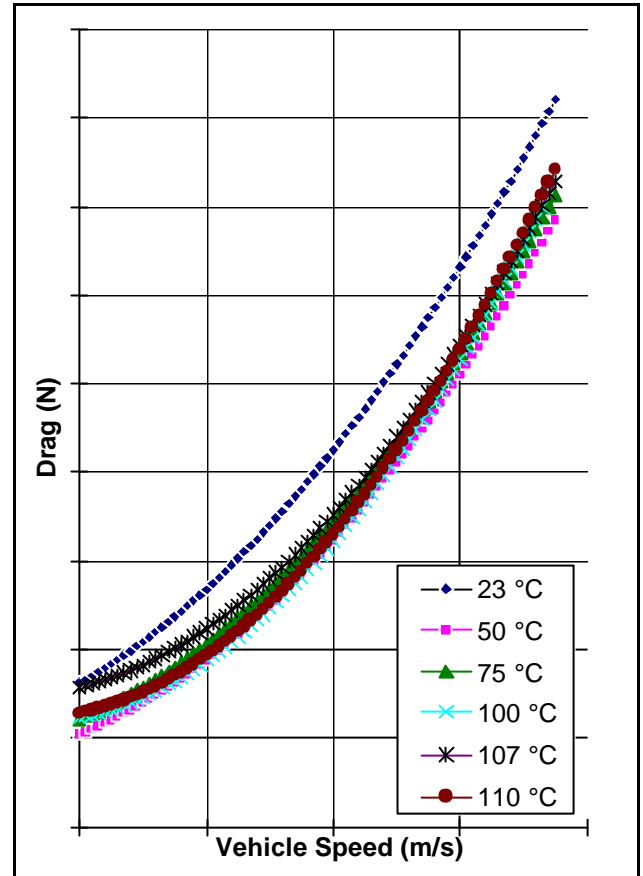


Figure 3. Un-driven wheel losses for a single wheel.

To provide input for the main coastdown analysis the losses were fitted with a quadratic.

RESULTS

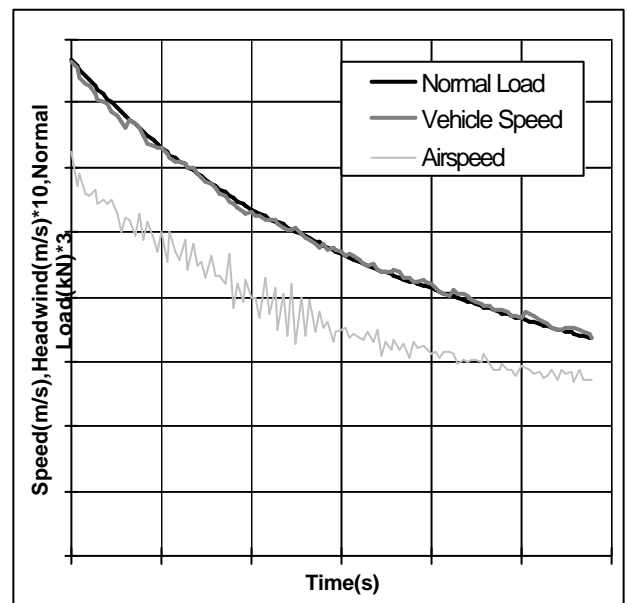


Figure 4. Example coastdown data.

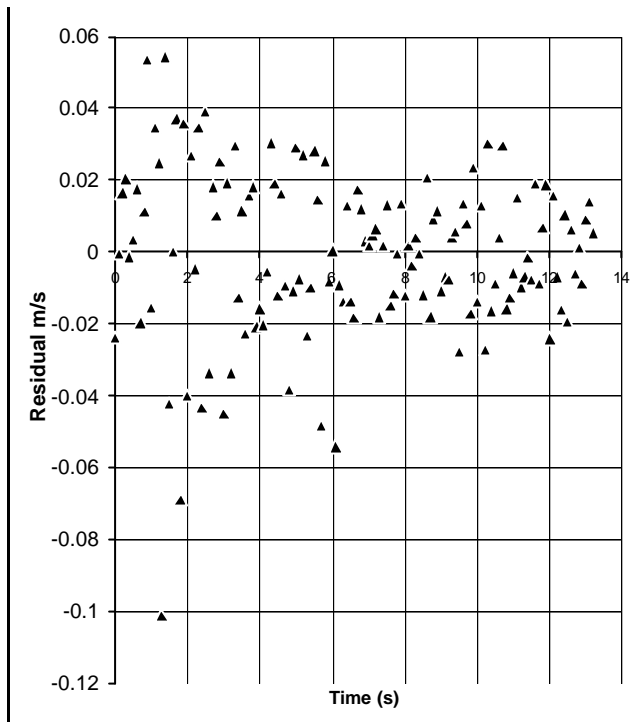


Figure 5. Coastdown residuals.

An example set of raw coastdown data is shown in figure 4.

The residuals (curve fitting errors) are illustrated for the same coastdown in Figure 5. These are an indication of the level of fit achieved in the analysis.

The residuals are largely distributed within ± 0.03 m/s indicating a very good fit of the model to the test data. The largest errors exist at the start of the tests (i.e. at high speed) and are considered to be largely due to track surface irregularities.

The converged coefficients for the four coastdowns are shown in Table 1. and the average values in Table 2. At the 95 per cent confidence level the A_d term has been determined with an accuracy of approximately 8 per cent, B_d with approximately 12 per cent and C_d approximately 2 per cent. Passmore¹ suggests that for a conventional car and this small number of tests accuracy of around 5 per cent, 20 per cent and 4 per cent respectively would be expected. The results are therefore very encouraging. The improved result achieved in this case may be attributed to the much larger drag forces experienced as compared with a conventional road car.

Table 1. Results from coastdown tests.

Test No.	A_d	B_d	C_d	RMS. Error (m/s)	Mean wind speed
1	0.0142	$7.33e^{-5}$	0.969	0.103	0.2 m/s.
2	0.0140	$7.17e^{-5}$	0.983	0.071	1.1 m/s.
3	0.0165	$9.17e^{-5}$	0.966	0.145	1.7 m/s.
4	0.0157	$8.55e^{-5}$	1.007	0.185	3.3 m/s.

Table 2. Summary results.

Coefficient	Mean	95% Confidence	Rig/ Tunnel values
A_d	0.0151	0.0151 ± 0.0012	0.0117
B_d	$8.06e^{-5}$	$8.06e^{-5} \pm 9.5e^{-6}$	$8.85e^{-5}$
C_d	0.981	0.981 ± 0.018	0.983

Comparing the results test to test, the repeatability is good, in particular for C_d which at the 95 per cent confidence level shows an error of less than 2 per cent. Test 4 yielded a slightly higher value of C_d , which is felt to be due to the higher wind speed for this test, possibly including some cross wind. Since a yawmeter was not used, it was impossible to account for this in the analysis.

The average values of the coefficients from the tests compare, for the most part, well with those obtained in the tyre dynamometer and wind tunnel tests. A_d from coastdown is approximately 30 per cent greater and B_d around 10 per cent lower than the tyre rig results, and C_d only 0.2 per cent higher than the wind tunnel value. Referring back to the development of the tyre model the sparse nature of the data throws some doubt on the value of A_d calculated from the tyre rig data particularly as it effectively involves extrapolating back to zero speed. In addition the method of disengaging the drive during the laboratory driveline tests was not consistent with that used on the track. In the first case neutral was selected and in the second the clutch was disengaged but the car remained in gear. Thus a higher A_d may indeed be expected.

To further assess the accuracy of the tyre model the coefficients A_d and B_d were removed from the analysis and replaced with the actual tyre rig data (as described in the section entitled coastdown analysis) which then yields only C_d . In this case the mean value was 0.999 an increase of 2.2 per cent. There is no compelling reason to attribute particular accuracy to the tyre rig data but this result does tend to show that the tyre model being used (EQ(4)) is sufficient for the purposes of coastdown analysis. It may also be suggested that an accuracy of around ± 2 per cent in C_d , as also suggested by the 95 per cent confidence limit, is realistic for the coastdown method.

CONCLUSIONS

1. A mathematical model defining the drag force acting on a Formula One car in coastdown has been developed.
2. A sophisticated test and analysis method has been developed and used to analyse real coastdown data.
3. For the vehicle in a medium downforce configuration the drag coefficients determined from Uni-directional coastdown analysis are: $A_d = 0.0151$, $B_d = 8.055 \times 10^{-5}$ and $C_d = 0.981$.
4. The repeatability is deemed to be good, with 95 per cent confidence limits of 8 per cent for A_d , 12 per cent for B_d and 2 per cent for C_d .
5. The results show good agreement with coefficients determined from tyre dynamometer and wind tunnel tests.

NOMENCLATURE

A	vehicle frontal area (m^2)
A_d	tyre drag coefficient
A_t	transmission loss constant (N)
A_u	un-driven wheel loss constant (N)
B_d	tyre drag coefficient (s/m)
B_u	un-driven wheel loss coefficient (Ns/m)
B_t	transmission loss coefficient (Ns/m)
C_{d_0}	aerodynamic drag coefficient - zero yaw
C_t	transmission loss coefficient (Ns^2/m^2)
$F_D(v)$	total drag function (N)
F_T	tractive effort (N)
g	gravitational acceleration (m/s^2)
K_d	variation of C_d with yaw (rad^2)
K_T	temperature correction coefficient (K^{-1})
M	vehicle mass (kg)
M_e	vehicle effective mass (kg)
T_o	observed ambient temperature (K)
T_s	standard ambient temperature (K)
t	time (s)
v	vehicle speed (m/s)
v_r	total relative airspeed (m/s)
v_{rm}	measured total relative airspeed (m/s)
δ_{fr}	Ride height front and rear (m)
α	track inclination (deg)
ρ	air density (kg/m^3)
ψ	yaw angle (deg)
γ_m	measured yaw angle (deg)

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