

ESTIMATION OF TRUCK DRAG FORCES FROM ROLL-DOWN TESTING

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Abstract

This paper presents a method that analyses the speed dependence of truck drag forces from roll-down tests. That is, the vehicle is rolled from a high initial speed to stop on a horizontal surface. The model assumes the speed dependence has squared (*A*), proportional (*B*) and constant (*C*) terms. The roll-down equation of motion is a second-order non-linear differential equation. A closed form solution is presented. The equation can be expressed in normalized form which allows comparison of different vehicle types and may provide new insights into the origin of drag forces.

A computer spreadsheet program has been developed that allows the three drag coefficients to be calculated from ten speed-time data points. Assuming that the coefficients are equally applicable to the roll-down and steady-state conditions, the method allows the drag power to be readily calculated. The affect on drag power that occurs when changes to the operating conditions are made can be determined and the contribution to the drag power of particular features can be estimated. In particular, the method allows the aerodynamic drag coefficient to be measured for large trucks, which is impractical by any other method.

Keywords: Truck drag forces, roll-down testing, Riccati equation, drag power losses, aerodynamic drag, GPA data logging.

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1 Introduction

The paper presents the theory of, and procedures for, the estimation of aerodynamic, tyre and engine drag forces from roll-down (or 'coast down') test measurements of speed against time. Roll down testing records the speed against time behaviour of an arbitrary vehicle that is let roll to stop on an approximately flat and horizontal roadway. The method is applicable to any vehicle type.

The procedures described in this paper allow the dependence of loss force on speed to be estimated. Tests can be conducted with different vehicle conditions such as weight, engine engagement, auxiliary brakes etc., which alter the relative contribution of the various drag forces. Hence the speed dependence of various contributions can be separated.

The quantification of loss components is important for development of vehicle enhancements that might reduce the aerodynamic, tyre or friction losses. Many authors have reported models of the characteristics of parasitic drag forces. Speed dependence is a key indicator of the characterization of the drag force.

It is usually assumed that three coefficients adequately describe the speed dependence of drag forces. The US EPA for example requires passenger car manufacturers to report the *A*, *B* and *C* coefficients, which are respectively the coefficients for speed², speed and constant drag force speed dependence.

Roll-down testing has been commonly applied to estimate the aerodynamic performance of light vehicles. The assumption is usually made that other drag factors can be ignored. This assumption is not valid for heavy trucks. For multi-combination trucks for example, the tyre drag loss may exceed the aerodynamic drag force. The paper allows for squared (aerodynamic), proportional (engine and tyres) and constant (rubbing friction) speed dependency.

2. Roll-Down Equation of Motion

The equation of motion applicable to a vehicle roll-down without driven power is

$$M \cdot dV/dt = C + BV + AV^2 = F_0 \{ C/F_0 + BV / F_0 + A V^2 / F_0 \} \quad (1)$$

where $F_0 = C + BV_0 + AV_0^2$ is the initial deceleration force (at $t = 0$). This model assumes that the drag-force speed dependence has three terms, which are constant (*C*), proportional (*B*) and quadratic (*A*). The analysis method is not limited to these three terms although the author is unaware of any evidence of other types of speed dependence. Note that there must be a non-zero constant term *C* if the vehicle is ever to stop rolling!

Setting $v = V/V_0$ and $\tau = M \cdot V_0 / F_0$ (or $\tau = V_0 / \{dV_0/dt\}$), then the equation of motion can be written in normal form as:

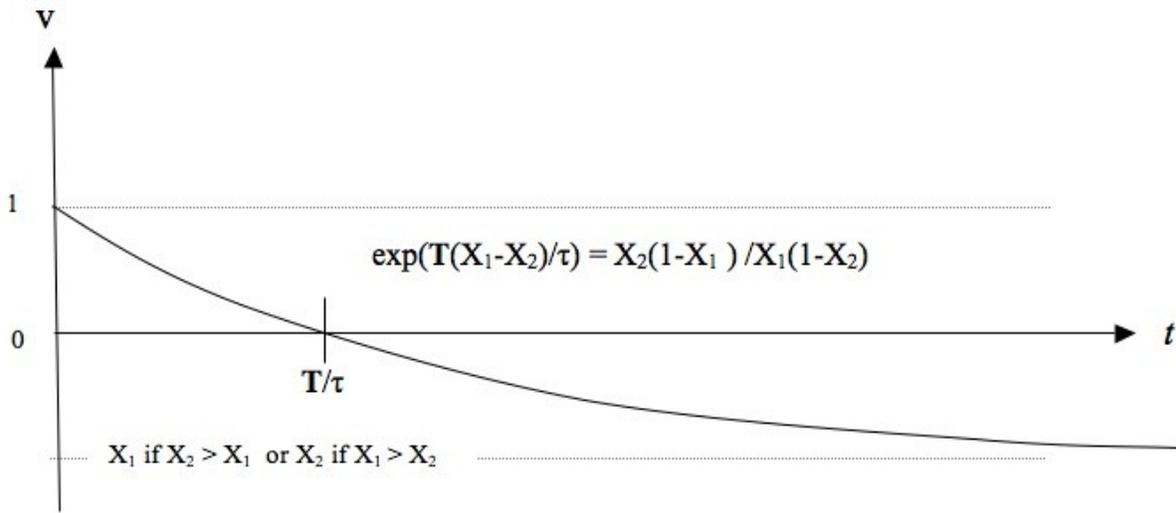
$$dv/dt = -\{\gamma + \beta v + \alpha v^2\} \quad t = t/\tau \quad (2)$$

The speed dependence coefficients are:

$$\gamma = C/F_o, \quad \beta = BV_o/F_o, \quad \alpha = AV_o^2/F_o \quad (3)$$

and $\gamma + \beta + \alpha = 1$. These ‘Riccati’ coefficients have the significance of the relative constant, proportional and quadratic drag force levels at the starting speed $v = 1$. Other higher- or lower-order speed-dependence terms can be accommodated by the method, however, for clarity of presentation they are not included here. Furthermore, the higher order terms are not needed to model real-world roll-down test performance.

The Riccati equation (2) has a closed-form solution which is illustrated in Figure 1.



$$X_1 = \{-\beta + \sqrt{\beta^2 - 4\gamma\alpha}\}/2\alpha \quad X_2 = \{-\beta - \sqrt{\beta^2 - 4\gamma\alpha}\}/2\alpha$$

$$T = \tau \ln\{X_2(1-X_1) / X_1(1-X_2)\} / (X_1 - X_2)$$

Figure 1 - The closed-form solution of the Riccati second order equation.

The use of the normal form allows the drag performance of different vehicle types and sizes to be compared as will be described in the next section.

3 The Drag Chart

The chart in Figure 1 is obtained by plotting the Riccati solutions for a range of the parameters α , β & γ . It shows solutions to Equation (2) for selected coefficients. The pure aerodynamic, pure proportional and pure braking curves are identified.

The recorded roll-down speed curves for a vehicle can be put into normal form if the initial acceleration and speed are known.

The time constant $\tau = V_o / \{dV_o/dt\}$ can be estimated from the initial data which enables the roll-down data to be expressed in terms of v and t .

The normalized roll-down curves for an unladen passenger bus, a laden delivery truck and a passenger car are shown on the chart in Figure 2. The characteristics are very different consistent with significantly different split of loss variation on speed.

The *Drag Chart* gives a visual indication of the relative size of the three parameters γ , β and α .

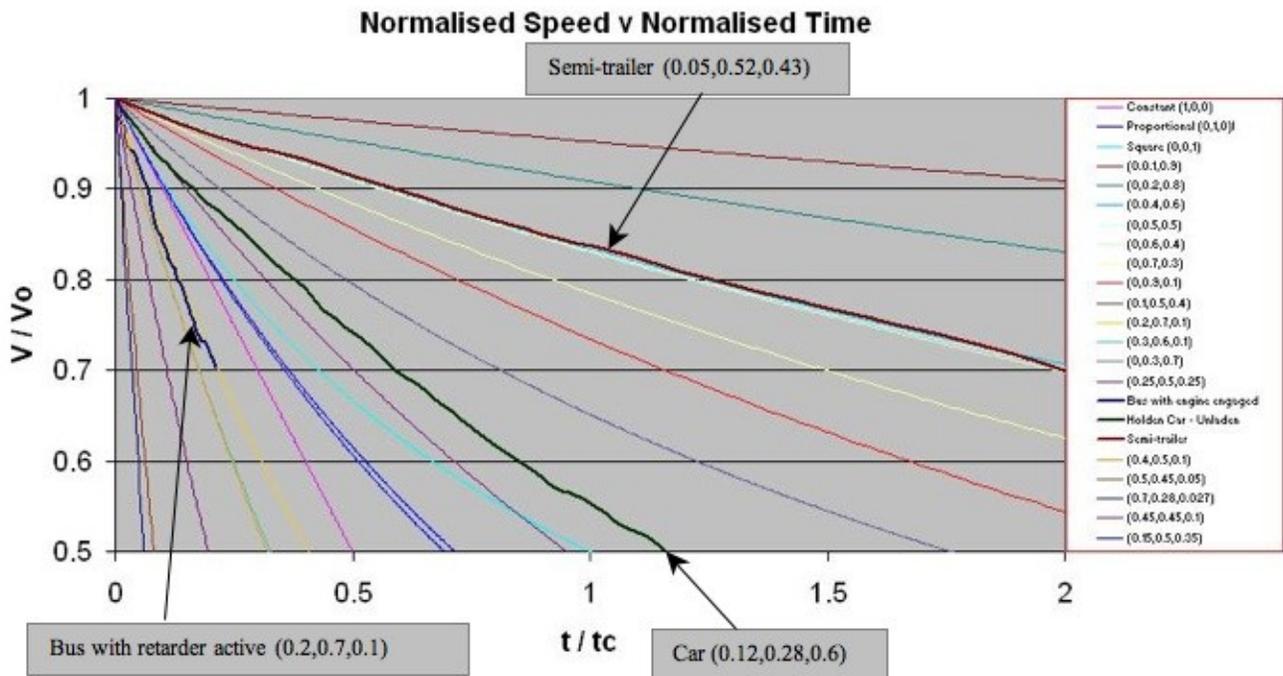


Figure 2 - The 'Drag Chart' shows a range of solutions to the Riccati equation.

4 Estimation of the Riccati Coefficients

More precise estimates of the Riccati coefficients can be obtained for the roll-down test results using the following algorithmic method:

- The vehicle is rolled down from high speed (V_0) on a flat roadway with negligible wind conditions. The test can be stopped when the speed falls to $\sim V_0/3$ although best results occur when the vehicle rolls to a stop.
- The times at which the speed falls to selected lower speeds is recorded. Ten speed points provide adequate coverage.
- The initial deceleration dV_0/dt is calculated using a fifth order Gaussian quadrature algorithm for the derivative, which is biased forward. Hence the time constant τ can be calculated.
- The deceleration at each speed value is computed using a fifth order Gaussian quadrature.
- Three widely spaced speeds are chosen. Estimates of the coefficients α , β and γ are obtained from the solution to the matrix equation:
- Several estimates for α , β and γ are obtained using different speed values. The estimates are averaged to improve accuracy. Variable wind conditions or roadway undulations will introduce inaccuracies.
- The calculations are done using a spreadsheet program.

$$\frac{d}{dt} \cdot \begin{vmatrix} v_a \\ v_b \\ v_c \end{vmatrix} = - \begin{vmatrix} 1, v_a, v_a^2 \\ 1, v_a, v_a^2 \\ 1, v_a, v_a^2 \end{vmatrix} \cdot \begin{vmatrix} \gamma \\ \beta \\ \alpha \end{vmatrix} \quad (4)$$

The Riccati coefficients of different vehicles or different operating conditions on the one vehicle can be sensibly compared if the roll down tests start from the same speed V_0 . The Riccati coefficients for the three test vehicles been calculated and are shown on Figure 1. All these vehicles were tested from a starting speed of 100km/h.

The three force components in Equation 1 can be calculated once the Riccati coefficients are known, by using the defining Equations (3). Note that the mass of the vehicle need not be known to calculate the Riccati coefficients but must be known to calculate the forces.

It is interesting to note that the Riccati Equation (2) has real solutions for only a limited range of the coefficient values (α , β , γ). Further work is needed to understand this behaviour.

5 Estimation of the Drag Effect of Variations

The drag power P as a function of speed V is:

$$P = C V + B V^2 + A V^3 \quad (5)$$

If two tests are done on the one vehicle with different operating conditions applying, then the relative effect can be calculated as follows:

$$\text{Condition 1: } P_1 = C_1 V + B_1 V^2 + A_1 V^3 \quad \text{Condition 2: } P_2 = C_2 V + B_2 V^2 + A_2 V^3 \quad (6)$$

The difference $P_2 - P_1$ can be attributed to the variation. This approach assumes that the transient performance that is inherent in Equation (1) can be used to calculate steady-state losses. Therefore it is assumed that the coefficients A , B and C which apply to roll-down tests are also applicable to steady-speed tests.

Figure 3 shows the roll-down traces for a ten-tonne delivery (van) truck that was tested with a tail-shaft retarder both active and inactive. The power difference can be attributed to retarder action because all other loss mechanism are changed. Figure 4 shows the power curves for the various cases.

Other variations that might be readily applied are:

- With and without engine engaged will separate out the engine drag.
- Laden and unladen (on a vehicle for which loading does not change the aerodynamic shape), will separate out the dependence of tyre losses on mass.
- With and without an aerodynamic feature and with the loading adjusted to keep the same weight will separate out the aerodynamic effect (if it is large enough).

The Riccati coefficients were calculated for the van tests. The parameters for the case with the engine disengaged and the retarder off are: $A = 3.9$, $B = 24.0$, $C = 280.1$.

6 Speed-Dependence Modeling of Truck Drag Losses

There are seven evident drag forces that act on heavy vehicles:

- aerodynamic drag,
- tyre drag force
- brake forces
- friction in bearings, differentials, engine and transmission,
- engine compression drag
- suspension friction drags
- uphill slope forces

The later two are not relevant to roll-down tests on smooth and flat roads and will be ignored. The other drag forces may be related to particular Riccati coefficients.

Speed Trace All Tests

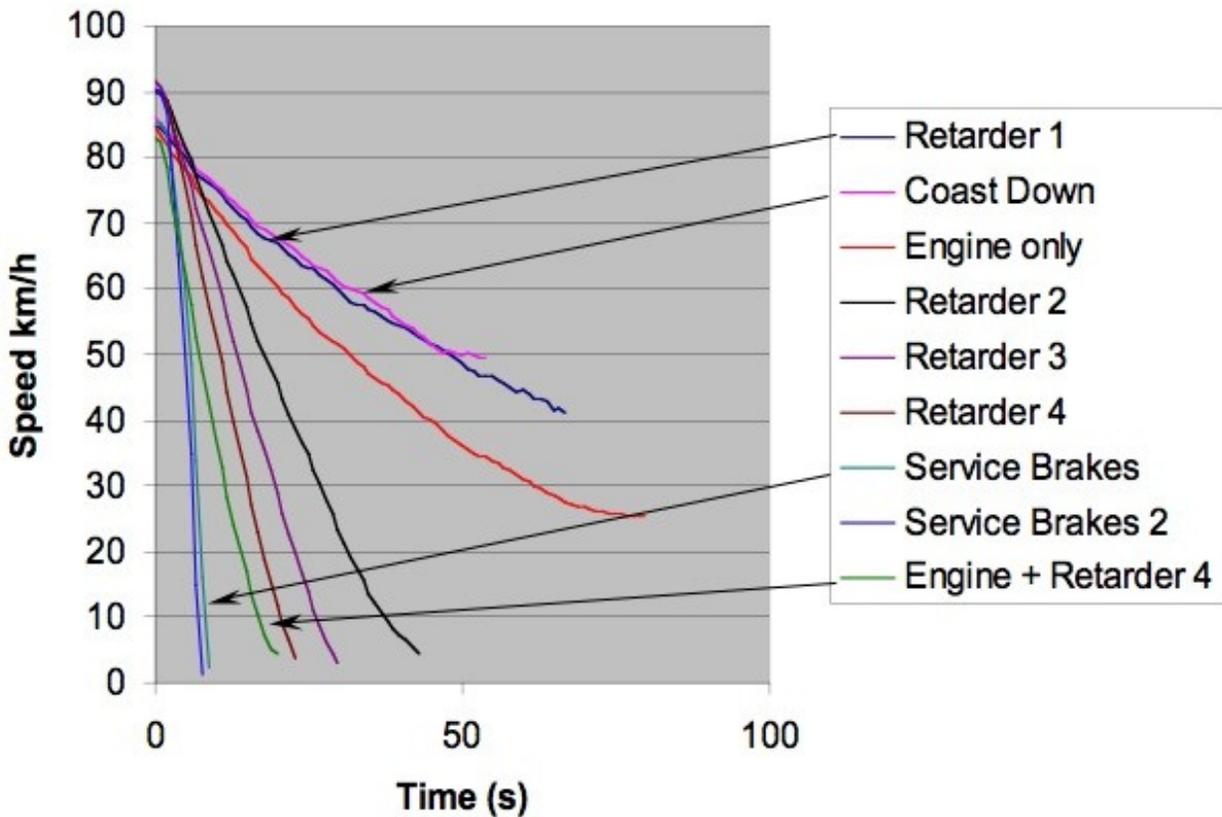


Figure 3 - Speed vs time measurements on a 10 tonne truck (van body) with various retarder and brake settings. The retarder has four settings. Retarder 1 was not working.

6.1 Aerodynamic Retardation

As is well known, the aerodynamic drag of a solid body is characterized by the drag co-efficient C_d :

$$F_d \sim -\frac{1}{2} \rho V^2 \cdot C_d \cdot \text{Area.} \quad (7)$$

Where F_d is the drag force (N), Area is the projected frontal area, V is the steady velocity of the fluid (m/s), ρ is the fluid density (kg/m^3) and C_d is the dimensionless drag coefficient. The published drag coefficients are in the range 0.7 – 1.2. It might be expected that multi-combination vehicles will have larger drag coefficients as a result of aerodynamic drag from successive trailers.

This relation (7) is only valid for high Reynold's numbers (>2000). At low velocity, particularly for a smooth surface, the drag force is more accurately proportional to V . For a heavy truck with the characteristic diagonal length of 4.7m. $V=27.8\text{m/s}^2$ and 17.8×10^{-5} . The Reynolds number is

7.3×10^5 . Therefore, the indicative flow is turbulent and the variation of loss force with velocity is proportional to V^2

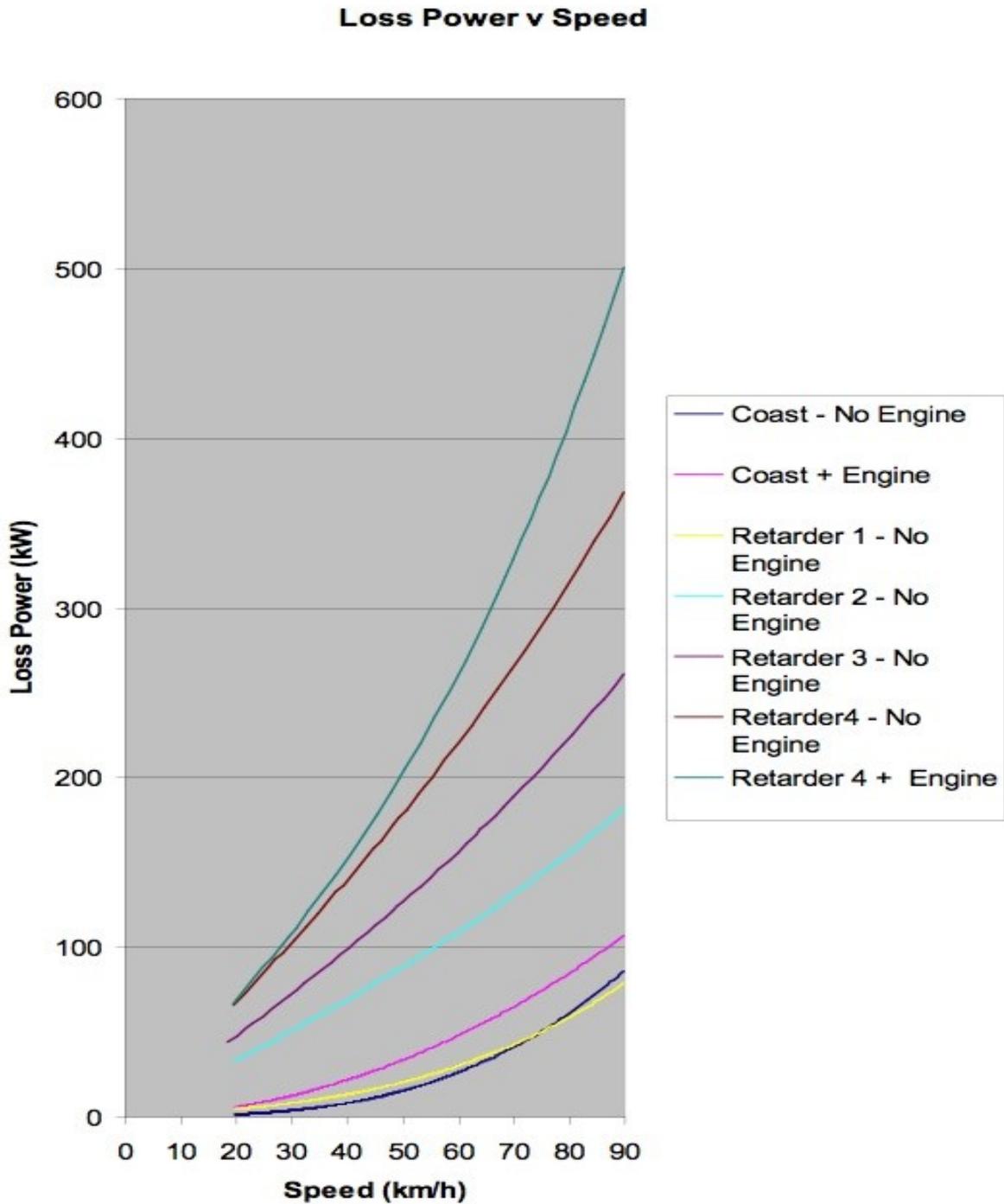


Figure 4 - Theoretical power v speed curves computed from the roll down data shown in Figure 3 using the theory presented here and the power equation Equation (5).

If it is assumed that the V^2 drag dependence is only due to aerodynamic drag then:

$$F_d = \frac{1}{2} \rho V^2 \cdot C_d \cdot \text{Area} = AV^2 \quad \text{and} \quad C_d \sim 2A / (\rho \cdot \text{Area}) \quad (8)$$

For a heavy truck the projected frontal area of $\sim 4 \times 2.5 = 10 \text{ m}^2$. The density of air at 20°C is about 1.2 kg/m^3 . Therefore:

$$C_d \sim 0.167A \quad (9)$$

For the delivery van (Figure 4) without the engine or retarder engaged, $A = 3.9$. Therefore, $C_d \sim 0.65$.

6.2 Brake Forces

Brake forces arise from friction forces between rubbing surfaces. First order theory describes the (moving) friction in terms of a friction coefficient. That is, the friction force per area is proportional to the normal pressure and speed is not a factor. This drag force is speed independent.

As the rubbing surfaces heat up the coefficient of friction will probably change. Hence, initial speed could be a factor because it determines the kinetic energy to be absorbed during a roll-down test and hence the potential for the heating of brake surfaces. That is, the test condition will influence the estimated friction level.

Test experience is that the deceleration that occurs during severe braking is approximately constant. This is illustrated by the service brake test lines in Figure 3 which are approximately straight.

During heavy braking the coefficient C is dominant. Its is predominantly due to braking forces.

6.3 Engine, Transmission, Differential and Bearing Losses

Two types of drag forces occur in the power-train. These are firstly rubbing losses due to friction in bearings, gears and cylinders. Secondly work done against the compression in the cylinders of the engine.

These losses have not been studied in detail on trucks. The compression losses are of particular interest because engine-compression brakes are routinely used and are relied upon for speed control on long downhill grades.

The roll-down method provides a tool that can be used to estimate the power absorbed at various speeds. Experience of the use of the method suggests that engine compression losses are best modeled by the proportional parameter B .

6.4 Tyre Losses

If it is assumed that the energy loss due to each tyre rotation is constant then the power absorbed by each tyre is:

$$P = E \cdot V / 2\pi R \quad (10)$$

where V is the speed (m/s), E is the energy loss per tyre revolution (J) and R is the tyre rolling radius (m). Hence the drag force is speed independent and is:

$$F_t = E/2\pi R \quad (11)$$

It is usually assumed that the tyre energy loss due to distortion of rubber is proportional to the load on the tyre. However, tyre inflation pressure is clearly important in this assessment. It seems likely that the tyre energy absorption will decrease with tyre inflation pressure because the tyre is capable of less distortion at high inflation pressure.

There must also be energy loss due to abrasion between the tyre rubber and the rough road surface. The abrasion increases with wheel slip. That is: $(V - \omega R)$ where ω is the rotational speed in radians/sec and V is in m/s.

The abrasion loss is greater during braking or traction because the transmission of force between tyre and road increases during these conditions.

A relationship for the tyre drag force that is used in simulations (UMTRI 1988) is:

$$F_t = \text{Load} \cdot C_p \cdot (6.10 + 0.11V) \cdot 10^{-3} \text{ (N)} \quad (12)$$

V is the speed in m/s. C_p is the tyre / pavement interaction factor which is taken to be 0.7 on a dry sealed road and 1.2 on a packed dry gravel road. Load is the total mass in kg at the tyre-road interface. For an 11R22.5 tyre loaded to 3t, rolling at 100km/h (27.78 m/s) on a sealed road, the equation predicts a drag force of 19.3 N.

A rolling resistance model that is often used for passenger cars (Rutman, 2009) is that the $C_{rr} \cdot C_p \cdot x$ weight. C_{rr} is the rolling resistance coefficient which is taken to be about 0.015 for a passenger car tyre.

Equation (12) predicts that the tyre losses contribute to both the constant (C) and proportional (B) parameters. The form of Equation (12) does not include slip speed term which suggests that it is only an approximation.

7 Practical Implementation

Roll down testing is easily done because of the development of GPS speed recording technology. Figure 5 shows the GT-11 hand held data recorder that the author has used to make the tests. The data is recorded and then transferred into a spreadsheet for analysis. During testing it is helpful to note the real time at the start of each test as this helps to sort out data from multiple tests.

The GPS recorder reports speed calculated on a 1s basis. The 1s increment is derived from the GPS satellite time base. The instantaneous speed data has an evident random variation of up to $\pm 10\%$. Calibration tests at constant speed have established the accuracy of time averaged data to about 2%. By using multiple data points to estimate the three Riccati parameters, the random errors are averaged. The estimates are believed to be accurate at or better than the 5% level.



Figure 5 - The GPS-11 data recorder. The display shows real time and instantaneous speed.

7 Conclusions

The roll-down method is simple to perform using existing, low cost GPS-based technology. It provides data that can be used to estimate the speed variation of drag forces.

The Riccati model for vehicle drag provides new understandings about the relative drag performance of vehicles with different weights and sizes. It naturally leads to the ‘*Drag Map*’ that provides a visual indication of the relative importance of the constant, proportional and square speed dependence terms.

Experience with the method has shown that higher-order speed dependence (cubic, quartic) can be neglected.

A spreadsheet program has been written that can be used to analyze the roll-down data. The program requires a minimum of ten data points (V , t) to be available. The spreadsheet facilitates the assessment of the origin of drag forces and is therefore useful as a tool for development of drag-reduction enhancements or the characterization of auxiliary brake performance.

Based on reasonable assumptions the roll-down method can be used to estimate the aerodynamic drag coefficient and the tyre-drag coefficient for a truck. These coefficients are difficult to

determine by any other method because of the practical difficulties involved in testing large trucks in a wind tunnel or on a dynamometer.

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