Running Resistance of Ore Trains in Sweden

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Summary: Running resistance of ore trains consisting of Uad type wagons is determined from full scale measurements on Malmbanan. Test are also run in curves with the Uad and an ore wagon equipped with a bogie allowing the axles to align themselves radially. Influence of speed, axle load, curve radii and train length is studied and quantified. The running resistance is parameterised and expressed in a general way so it can be calculated for any Swedish ore train consisting of Uad-type wagons. The study shows that the increase in running resistance is linear due to increasing axle load on tangent track and train length. The increase in resistance due to curves is significant and increases as the curve radius decreases. If the axles align themselves radially the curve resistance reduces by 40%, compared with the Uad. The results show which parameters in a running resistance formula should be paid extra attention to when constructing a train model for simulation purposes. A comparison is made between ore trains and ordinary Swedish loco-hauled freight trains. In the paper a review of the study will be made with conclusions.

Index Terms: Running resistance, Ore Train, Curve resistance, Rolling resistance, Air drag, Power consumption, Running Time.

NOTATIONS

A	resistance constant [N]
A_f	frontal cross section area of train [m^2]
B	resistance coefficient [Ns/m]
C	resistance coefficient [Ns^2/m^2]
C_D	air drag coefficient
E	energy [Ws]
F_D	air drag [N]
F_G	grade resistance [N]
F_I	inertia resistance [N]
F_{Mc}	curve resistance [N]
F_{Mt}	rolling resistance on tangent track [N]
F_R	running resistance [N]
$\bar{F}$	mean force [N]
H	relative factor accounting for rotary inertia
L_T	total length of train [m]
Q	axle load of wagon [kN]
R	curve radius [m]
g	gravitational acceleration [m/s^2]
h	track altitude [m]
m	mass [kg]
n_{ax}	total number of axles
n_c	total number of axles running in curve
v	speed [m/s]
$\bar{v}$	mean speed [m/s]
x	measuring position [m]
Δt	travel time between measuring positions [s]
Δx	measuring distance [m]
ΔX	evaluation distance [m]

1 INTRODUCTION

The magnitude of the forces acting on a train against its direction of travel are known as running resistance, F_R. It is a must to know the running resistance of trains for determining power requirements, and running times by means of simulation. Moreover, running resistance is also a very important parameter when designing a Driving Advice System, DAS or an Automatic Train Operation system, ATO, which purpose is to improve punctuality and reduce the energy consumption by means of energy efficient driving. Running resistance can be divided into the following main categories

1. Mechanical rolling resistance on tangent track, F_{Mt}, due to mechanical energy dissipation in vehicle, track and the contact areas between wheels and track.

2. Mechanical curve resistance, F_{Mc}, which is the increment in rolling resistance as a train is rounding a curve.

3. Aerodynamic drag, F_D.

4. Grade resistance, F_G; as ascending a grade a train will experience a resistive force due to gravity.

5. Inertia resistance, F_I. Can be interpreted as the extra tractive effort required for acceleration due to the effect of inertia, ref. [1].

Energy is dissipated due only to mechanical rolling resistance, curve resistances and aerodynamic drag. Energy for overcoming grades and inertia can be recovered while descending grades or coasting.

Experimental findings show that running resistance can be quantified according to ref. [2, 3, 4, 5, 6] with adequate accuracy as a function of speed by a second degree polynomial

$$F_R = A + Bv + Cv^2 \qquad (1)$$

where v is the train speed in m/s. The coefficients A, B and C are in fact not constants; they vary with type of train, track, wheel-rail friction etc.

Mechanical resistance is generally accepted, [1, 2], as covered by term A and Bv in Equation (1). Term Cv^2 is considered to cover aerodynamic drag, except air momentum drag, believed to depend linearly upon speed. Air momentum drag is thus also covered by term Bv.

Aerodynamic drag, the part which is dependent upon speed squared, is usually written for no wind conditions as

$$\begin{aligned} F_D &= \frac{1}{2}\rho A_f C_D v^2 = \\ &= \frac{1}{2}\rho A_f (C_p + C_S L_T) v^2 = Cv^2 \quad [\mathrm{N}] \end{aligned} \qquad (2)$$

where ρ is the density of air, A_f the frontal area of train, C_D is the air drag coefficient, C_p pressure drag coefficient, C_s friction drag coefficient and L_T is the total train length. Since it is not always a simple task to determine the frontal area of a test train, it is convenient to express coefficient C as air drag area $C_D A_f$

$$C_D A_f = (C_p + C_S L_T) A_f = \frac{2}{\rho} C \ [\mathrm{m}^2] \qquad (3)$$

The terms A, Bv and Cv^2 cover various complex and interrelated physical phenomena. The magnitudes of the coefficients determined from experiments, are affected by resistive forces that may vary with other powers of speed than those in Equation (1).

In this paper, the running resistance of an ore train is determined from full scale tests. The objective is to form a general expression for the running resistance of an ore train based on Equation 1. The expression takes into account the influence of axle load, speed and train length. Curve resistance is also evaluated. The obtained results for the ore train are compared with other results from tests performed with freight trains in Sweden.

In section 2, a brief description of the test methodology, conditions and tested train is found. Thereafter are the evaluated experimental results presented in section 3. In section 4, a general expression for the running resistance is formed for an arbitrary ore train and in section 5 is a comparison made between ore and freight trains. The conclusion are in section 6.

2 TEST METHODOLOGY, CONDITIONS AND TRAINS

2.1 Test methodology

Train running resistance, F_R, is associated with energy dissipation. This dissipation equals the work done by F_R over a travelled distance.

If a coasting train's kinetic and potential energy is determined at successive measuring positions, $x_1..x_a..x_{a+k}..$, along the track separated by a measuring distance $\Delta x = x_{a+1}-x_a$ from each other, as shown in Figure 1, the difference in the train's total energy between these measuring positions can be calculated. The energy must be determined with respect to some point of reference on the train.

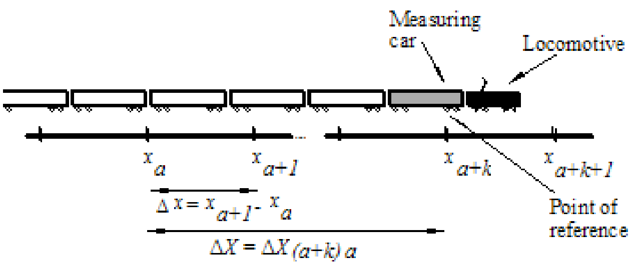

Figure 1: Measuring positions along the track [2].

Now, the energy dissipation corresponding to the mean running resistance, $\overline{F}_{R_{(a+k)a}}$, can be calculated between two arbitrary measuring positions, x_a and x_{a+k}, separated by the evaluation distance of $\Delta X_{(a+k)a}$. The mean running resistance is resolved from the energy balance equation

$$E_{kin_a} + E_{pot_a} = E_{kin_{a+k}} + E_{pot_{a+k}} + \overline{F}_{R_{(a+k)a}} \Delta X_{(a+k)a} \quad (4)$$

where E_{kin} and E_{pot} is the kinetic and potential energy of the train, respectively. This is provided that no energy is supplied from any external source and all vehicles of the train have the same speed. In order to estimate a train's potential energy at a measuring position the train mass has to be distributed over the length of the train. The track altitude, h, at each vehicle's local point of reference in the train must be determined. The total mean running resistance for a coasting train and the corresponding mean speed, $\overline{v}$, between two arbitrary measuring positions, x_a and x_{a+k}, is calculated by

$$\overline{F}_{R_{(a+k)a}} = \frac{1}{\Delta X_{(a+k)a}} \left(\sum_{i=1}^{n_v} m_i \left(\frac{1}{2} (1 + H_i)\left(v_a^2 - v_{a+k}^2\right) + g\left(h_{i_a} - h_{i_{a+k}}\right)\right)\right)$$

$$\overline{v}_{(a+k)a} = \frac{\Delta X_{(a+k)a}}{\Delta t_{(a+k)a}} \quad (6)$$

where i is the vehicle number and n_v is the total number of vehicles in the train set. m_i is the mass and H_i is a factor accounting for the rotary inertia of vehicle i. $\Delta t_{(a+k)a}$ is the travel time between measuring positions x_a and x_{a+k}.

By shifting $\Delta X_{(a+k)a}$ forward, $a = 1..j$, along the measuring section by Δx the mean running resistance with its corresponding mean speed can be estimated successively for each ΔX until the end of the measuring section is reached, or the train stops by itself. In this way j number of data pairs of $\left(\overline{v}, \overline{F}_R\right)$ are formed. The data pairs can then be used for fitting a polynomial having the form according to Equation 1 for each test run by means of the method of least squares.

Influence of ambient wind upon the determined running resistance can be minimised by averaging polynomials from test runs which are run in each direction along the same measuring section during similar wind conditions. The difference between wind averaged C coefficients and C coefficients evaluated for almost zero wind conditions is approximately less than ± 3% for freight trains [2].

Theoretically, the total maximal relative error is approximately ±8% [2]. However, from full-scale tests a standard error of less than 3% is achieved for test run pairs. The method is sensitive, like other methods, to precision errors in speed and in determined track altitude.

2.2 Tested wagons and train

The data for the tested ore wagons Uad (Uad 014-8) and MV2000 (Uanoo 9227000-0, Rev R4-95) and for the test train consisting of 1 Rm loco + 10 Uad are shown in Tables 1 and 2 respectively [7]. *Q* is the mean axle load of a wagon or the test train in metric tonnes. Before the tests started, every single wagon was weighted [7]. The data was provided by the former SJ Rolling Stock Laboratory, SJ/MTL, now Interfleet Technology AB.

The Uad wagon tested is equipped with so called ‘’three-piece bogies’’ and is shown in Figure 2. The length of the wagon is 8.4m

The MV2000 was an ore wagon tested on Malmbanan. It looks similar to an Uad wagon but is longer, 9.8m. Also, MV2000 was equipped with the ASF AR-1 bogie [8] allowing the axles in the bogie to align themselves radially in curves. Three load cases were studied for the MV2000, as shown in Table 1. *Q* is the axle load.

Figure 2: Uad ore wagon.

Table 1

Data for ore wagon Uad and MV2000.

	Axles	*Q* [t]	Mass [t]	Length [m]
Uad	4	24.8	99.2	8.4
MV2000-1	4	5.3	21.2	9.8
MV2000-2	4	25.0	100.0	9.8
MV2000-3	4	29.7	118.8	9.8

Table 2

Data for the ore train.

Configuration	Axles	*Q* [t]	Mass [t]	Length[m]
Loco Rm + 10 Uad	40	24.8	1090.0	100

2.3 Conditions

The full scale tests with the ore train and wagons were performed on Malmbanan during 1995-06-06 -- 1995-06-14, on a track-section close to Kiruna on the line Kiruna-Gällivare.

Tests were run on tangent track and in curves having radii of 595m and 900m. The length of the curves were in the range 400–650m. The track was a CWR on concrete sleepers with a 55 cm spacing. The mass of rail was 50 kg/m. Data on track stiffness was not available.

The track data with respect to grades, altitude and curve radii was measured, checked and exclusively provided for the tests by the Swedish National Rail Administration.

The rails on the test sections were not lubricated. Only tests conducted during dry-rail conditions are evaluated [7].

The direction and velocity of the ambient wind was recorded continuously during the tests. The velocity of the wind was within the range of 0 - 5 m/s.

3 RESULTS

Measurements for determining speed and position of the wagons and train tested were performed and recorded by the former SJ Rolling Stock Laboratory, SJ/MTL, now Interfleet Technology AB.

The results presented are wind minimised and the total running resistance of a coasting train on level track is expressed as a function of speed by

$$F_R \approx F_{Mc} + A + Bv + Cv^2 \qquad (7)$$

Only mechanical rolling resistance, mechanical curve resistance, and air drag is evaluated. Curve resistance is determined with respect to axle load and curve radius and is separated from the mechanical rolling resistance. Coefficients *A*, *B* and *C* are determined with respect to variation in axle load and train length.

3.1 MV2000 on tangent track

The wind minimised results for the coefficients are shown in Table 3, and the running resistance as a function of speed and axle load is shown in Figure 3.

Table 3
MV2000. Results from tests on tangent track.

Load case	*Q* [t]	A [N]	B [Ns/m]	C [Ns^2/m^2]
MV2000-1	5.3	450	-2	4.7
MV2000-2	25.0	1100	-2	4.7
MV2000-3	29.7	1300	-3	4.4

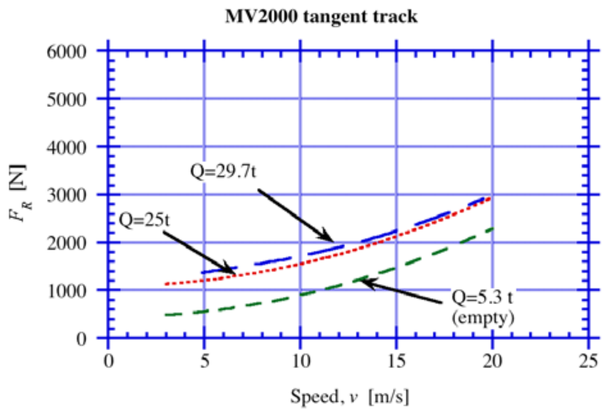

Figure 3: Impact of axle load and speed on running resistance for MV2000.

Variation of axle load, reveals that coefficient *A* varies approximately linearly with change in axle load, on the tracks tested, see also Figure 8. Coefficient *A*, as a function of axle load, *Q*, and number of axles, n_{ax}, for a four axle ore wagon, is approximated by

$$A \approx \sum_{i=1}^{n_{ax}} (66 + g \cdot 0.9 \cdot Q_i) \quad \text{[N]} \qquad (8)$$

$$5.3 \le Q_i \le 29.7\text{t}\,,\ v > 3 \text{ m/s}$$

As shown in Table 3 no systematic variation of coefficient *B* due to axle load can be distinguished, see also Figure 9. This may indicate that on a stiff CWR track the main part of coefficient *B* originates from portions of air drag not covered by Cv^2 [2]. Therefore, coefficient *B* may be expressed as a function of total train length [2] rather than train mass.

Coefficient *C*, which mainly originates from the air drag is about 4.7. For the load case 3, the *C* coefficient differs from the other two cases by 6-7%.

3.2 MV2000 in curves

Only load case MV2000-1 and MV2000-2 was tested in curves. The wind minimised results are shown in Fig 4. The evaluated mean curve resistance is for the MV2000

$$R = 595\text{m}: \quad F_{Mc} \approx \begin{cases} 1.5 \cdot g \cdot \sum_{i=1}^{n_{ax}} Q_i \quad \text{[N]; Q} \approx 5.3\text{t} \\ 1.1 \cdot g \cdot \sum_{i=1}^{n_{ax}} Q_i \quad \text{[N]; Q} \approx 25.0\text{t} \end{cases} \qquad (9)$$

$$R = 900\text{m}: \quad F_{Mc} \approx \begin{cases} 0.6 \cdot g \cdot \sum_{i=1}^{n_{ax}} Q_i \quad \text{[N]; Q} \approx 5.3\text{t} \\ 0.9 \cdot g \cdot \sum_{i=1}^{n_{ax}} Q_i \quad \text{[N]; Q} \approx 25.0\text{t} \end{cases} \qquad (10)$$

where *R* is the curve radius in metres.

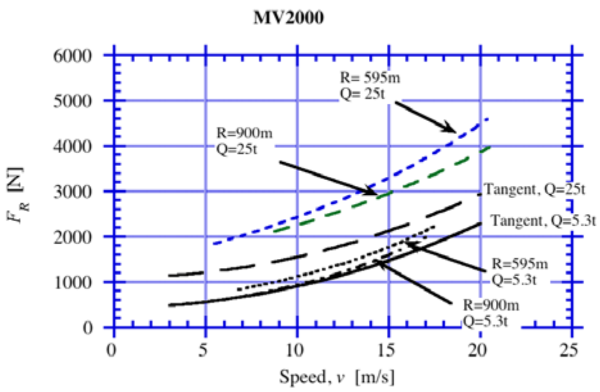

Figure 4: Impact of curves, axle load and speed on running resistance for MV2000.

3.3 Uad on tangent track

The wind minimised result for the *A*, *B* and *C*-coefficients of a single Uad wagon on tangent track is shown in Table 4.

Table 4

Uad. Result from tests on tangent track.

Q [t]	A [N]	B [Ns/m]	C [Ns²/m²]
24.8	1100	-2	4.7

The results are the same as for the MV2000-2, see Table 3.

3.4 Uad in curves

The evaluated mean curve resistance is for the Uad with the axle load of 24.8t

$$R = 595\,\mathrm{m}: F_{Mc} \approx 1.7 \cdot g \cdot \sum_{i=1}^{n_{ax}} Q_i \text{ [N]} \qquad (11)$$

$$R = 900\,\mathrm{m}: F_{Mc} \approx 1.5 \cdot g \cdot \sum_{i=1}^{n_{ax}} Q_i \text{[N]} \qquad (12)$$

$Q \approx 24.8\mathrm{t}$

The running resistance in curves and on tangent track of a single Uad wagon is shown in Figure 5. The axle load is 24.8 tonnes.

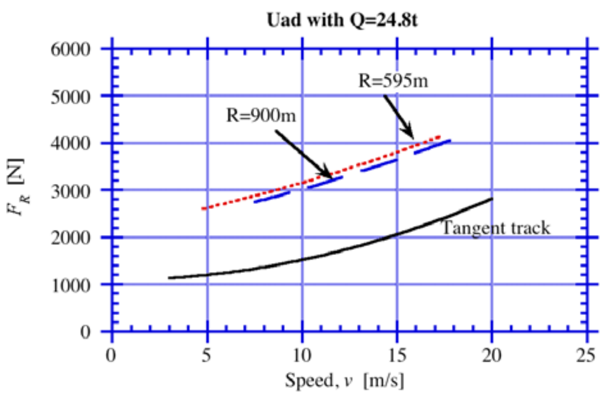

Figure 5: Uad. Impact of curves, axle load and speed on running resistance.

3.5 Test train on tangent track and in curves

Results from tests performed with a whole train are more reliable compared with results from tests with a single wagon. A single wagon which may not be representative from the point of running resistance, will probably not affect the final results for a whole train in the same severe way as if it would do if only the wagon was tested alone.

The wind minimised test result for the test train run on tangent track is shown in Table 5.

Table 5

Test train. Result from tests on tangent track.

Q [t]	A [N]	B [Ns/m]	C [Ns²/m²]
24.8	12000	20	16.75

Coefficient *A*, shows good agreement with results obtained from test with a single Uad wagon. If the contribution of the locomotive is subtracted, approx. 2000N [2], the *A* coefficient results in approx. 1000N/wagon.

Coefficient *B* is relatively small and has almost no impact on the running resistance. It can therefore in most cases be omitted. However, the coefficient *B* can be expressed [1, 2] as a function of train length, L_T, by

$$B \approx 0.2 \cdot L_T \text{ [Ns/m]} \qquad (13)$$

It has been shown experimentally, e.g. [2, 4, 5] that coefficient *C* can be divided into two parts. One part that is constant and one part that varies with the length of the train. From independent tests performed with loco hauled passenger and freight trains having different lengths it is concluded that the air drag increases linearly with the train length [2, 4, 5, 9]. See also Figure 10. Therefore, it is assumed here that the air drag of ore trains increases linearly as well. The evaluation of coefficient *C* for the ore train results in

$$C \approx 5.4 + 11.4 \cdot 10^{-2} \cdot L_T \quad [\mathrm{Ns^2/m^2}] \qquad (14)$$

The results from tests on tangent track and in curves are shown in Figure 6.

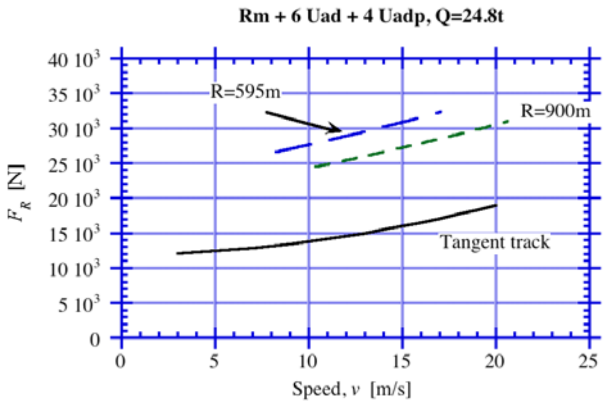

Figure 6: Running resistance for the test train as function of speed and curve radius.

The average curve resistance of the test train is approximated by

$$R = 595\text{m}: F_{Mc} \approx 1.3 \cdot g \cdot \sum_{i=1}^{n_c} Q_i \text{ [N]} \qquad (15)$$

$$R = 900\text{m}: F_{Mc} \approx 1.0 \cdot g \cdot \sum_{i=1}^{n_c} Q_i \text{ [N]}$$
$$n_c \le n_{ax}, Q \approx 24.8 \text{ t} \qquad (16)$$

where n_c is the total number of axles of the train running in the curve.

4 GENERAL RUNNING RESISTANCE FOR ORE TRAINS

If the assumption is made that the curve resistance of ore wagons can be expressed according to a formula developed by Röckl [1, 6, 9], then the curve resistance can be expressed as a function of curve radius and mass of train. By adapting the formula, the mean curve resistance for the part of an ore train, consisting of Uad wagons, which runs in a curve is expressed by

$$F_{Mc} \approx \frac{780}{R-55} g \cdot \sum_{i=1}^{n_c} Q_i \text{ [N]} \qquad (17)$$

R>350m, $n_c \le n_{ax}$

The curve resistance, calculated by Equation (17), differs from the measured by approximately ±10% for the curve radii tested, 595 and 900m.

Similarly, for a train consisting of MV2000, the part that is running in a curve can be approximated by

$$F_{Mc} \approx \frac{500}{R-55} g \cdot \sum_{i=1}^{n_c} Q_i \text{ [N]} \qquad (18)$$

if the assumption is made that the curve resistance is approximately 35% lower than for the Uad. This assumption can be made if Equations 11 and 12 are compared with Equations 9 and 10 with Q=25t, respectively.

The coefficient *A*, which represents the mechanical rolling resistance, as a function of axle load on tangent track is according to Equation (8),

$$A \approx \sum_{i=1}^{n_{ax}} (66 + g \cdot 0.9 \cdot Q_i) \text{ [N]} \qquad (8)$$

$5.3 \le Q_i \le 29.7\text{t}$, $v > 3$ m/s

The magnitude of coefficient *A* of one Uad wagon on tangent track is approximately the same as for an MV2000 with *Q*=25t. See Table 3 and 4.

Coefficient *B* can be expressed according to Equation (13),

$$B \approx 0.2 \cdot L_T \text{ [Ns/m]} \qquad (13)$$

Since the coefficient *C*, which represents the air drag, is approx. the same for the Uad and MV2000, it is assumed here that the evaluated *C*-coefficient for the Rm loco + Uad wagons also represents a train consisting of MV2000

$$C \approx 5.4 + 11.4 \cdot 10^{-2} \cdot L_T \text{ [Ns}^2\text{/m}^2\text{]} \qquad (14)$$

Hence, except for the grade and inertia resistance, the running resistance of an ore train can be calculated by Equation 7.

From tests with freight trains hauled by a locomotive of type Rc4 it is concluded that the Rc4 contributes to the rolling resistance with approximately 2000 N [2, 9]. The contribution to the rolling resistance of one locomotive of type Rm is most likely about the same, even though it is heavier. Externally, the two locomotives are almost identical, so the contribution to the air drag should be about the same. The relatively new locomotive of type ''Iore'' was not tested.

5 COMPARISON WITH FREIGHT TRAINS

The running resistance of loco-hauled freight trains in Sweden is investigated in [2, 9]. Freight trains consisting of 2-axled covered type Hbis and open type Oms wagons are used here for the comparison. The freight wagons, forming a mixed train consist, are shown in Figure 7.

Figure 7: Freight train of mixed consist. Covered type Hbis wagons and open type Oms wagons.

A comparison between the change in *A* due to change in axle load is shown in Figure 8. The change in coefficient *A* is approximately linear with respect to the change in axle load.

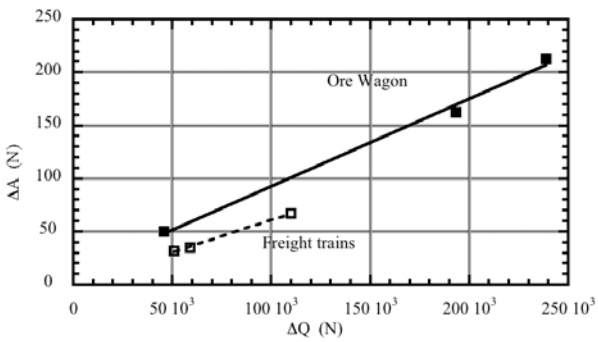

Figure 8: Change in *A* due to change in axle load.

The *A* coefficient for the freight trains [2, 9] is approximated by

$$A \approx \sum_{i=1}^{n_{ax}} (65 + g \cdot 0.6 \cdot Q_i) \text{ [N]} \qquad (19)$$

The *B* coefficients for different axle loads, masses, are shown in Figure 9. No impact of axle load can be distinguished. Trains F4-F6 differ only with respect to axle load.

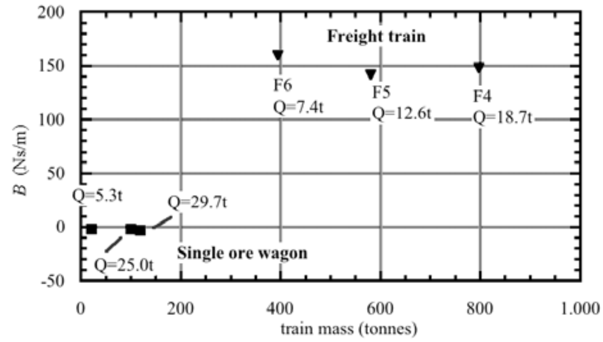

Figure 9: Coefficient *B* on tangent track for different train masses [9].

The air drag areas, C_DA_f, for ore trains, different freight, loco-hauled passenger trains and the high speed train X2 are shown for comparison in Figure 10.

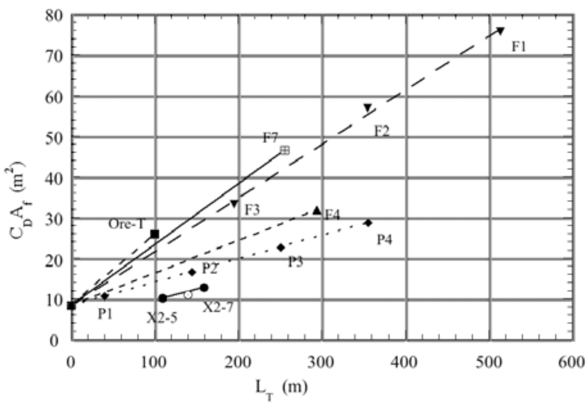

Figure 10: Air drag area, C_DA_f, for different trains as function of train length. Ore-T= ore train tested, F7= Oms wagons, F1-F3=mixed consist, F4=covered Hbis wagons,P1-P4=loco hauled passenger trains, X2-5 and X2-7=high speed train [9].

Figure 10 reveals that ore trains have the highest air drag area, thus the highest air drag among the trains tested. Also, a freight train consisting of only loco + open type Oms wagons, which are equipped with poles standing up from the side walls, has a higher air drag than a freight train having a mixed consist which is shown in Figure 7.

6 CONCLUSIONS

Tests are run with Uad and MV2000 ore wagons, in curves having the radii of 595 m and 900 m. The tests reveal that curve resistance of an MV2000 is on an average 30 - 40% lower than for an Uad wagon, at speeds lower than 15 m/s. The difference in curve resistance between MV2000 and Uad is believed to be due to the type of bogie. MV2000 has bogies where the axles aligns themselves approximately radially in curves, while an Uad wagon is equipped with ordinary three-piece bogies.

The curve resistance contributes significantly to the running resistance. For the Uad, the magnitude of the curve resistance, in the curves tested, is approximately 80% of its rolling resistance determined on tangent track.

The mechanical rolling resistance on tangent track increases approximately linearly with the axle load for ore, and freight trains, on the tracks tested.

Coefficient *B,* which represents the part of the running resistance which increases linearly with speed, shows no variation due to variation in axle load. This is independently shown for the ore and freight trains. The contribution of this part to the total resistance is small.

Air drag, which is represented by coefficient *C*, is assumed to increase linearly with the length of the ore train tested. Independent tests show that this is true for other loco hauled trains, where the air drag increases approximately linearly with train length.

Compared with other trains, the ore train tested shows to have a relatively high air drag. The impact of ambient wind is minimised.

7 ACKNOWLEDGEMENTS

The author wishes to express his gratitude to the staff of the former SJ Rolling Stock Laboratory, SJ/MTL, now Interfleet Technology AB, for appropriate measurements during the tests. In particular Mr. Sven-Erik Gustavsson and Mr. Lars Andersson.

Mr. Lars Andersson ''in action'' supervising the measurements.

Swedish National Rail Administration (Banverket), for providing track data.

LKAB for providing the ore wagons.

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