Equations for Calculating Resistance

Open Rails calculates resistance values for locomotives and rolling stock based on the following information in the eng and wag files:

ORTSDavis_A	N
ORTSDavis_B	N/m/s
ORTSDavis_C	$N/m/s^2$

The units most often used for published data differ from these in that they use kg(force), tonnes, km/h, lb(force), tons(US), tons(UK) and mph. Some of the equations are also written in such a way that some rearrangement may be needed to identify the coefficients A, B and C. The first section below gives a list of formulae that can be used to calculate the information needed by Open Rails.

Contents

1. Calculating Parameters for Open Rails

M – mass (tonnes)
n – number of axles
A – cross sectional area (m^2)
S – surface area (m^2) (perimeter x Length)
L – length (m)

1.1.1 SNCF General Formula

ORTSDavis_A	=	$\lambda \sqrt{(10 M n)}$	
ORTSDavis_B	=	3.53 M	
ORTSDavis_C	=	$k_1 A + k_2 S$	*for leading vehicle*
	=	$k_2 S$	*for following vehicles*

λ is generally between 8.83 and 14.7 depending on bogies and journals.
k_1 is generally between 0.116 and 0.255 depending on streamlining of nose and tail.
k_2 is generally between 0.00256 and 0.00352 depending on streamlining of surface.

1.1.2 SNCF Empirical Formulae for Specific Rolling Stock

For Diesel and Electric Locomotives

ORTSDavis_A = 0.65 M + 13 n
ORTSDavis_B = 3.53 M
ORTSDavis_C = 3.81

For BB 9001 Electric Locomotive (80 tonnes)

ORTSDavis_A = 13 M
ORTSDavis_B = 0.35 M
ORTSDavis_C = 0.0459 M

For CC 6001 Electric Locomotive (120 tonnes)

ORTSDavis_A = 12.5 M
ORTSDavis_B = 0.35 M
ORTSDavis_C = 0.0306 M

For Passenger Carriages on Bogies (Profilidis)

ORTSDavis_A = 14.7 M
ORTSDavis_B = 0
ORTSDavis_C = 0.0282 M

For Standard UIC Passenger Carriages (Allenbach et al)

ORTSDavis_A = 15 M
ORTSDavis_B = 0
ORTSDavis_C = 0.0272 M

For Standard UIC Passenger Carriages (Profilidis)

ORTSDavis_A = 12.3 M
ORTSDavis_B = 0
ORTSDavis_C = 0.0202 M

For Corail Passenger Carriages (Allenbach et al)

ORTSDavis_A	=	12.5 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.0194 M

For 4-wheeled Passenger Carriages and Express Freight Vans

ORTSDavis_A	=	14.7 M
ORTSDavis_B	=	0
ORTSDavis_C	=	between 0.0530 M and 0.0635 M

For Block Freight Trains (Profilidis)

ORTSDavis_A	=	11.8 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.0318 M

For Block Freight Trains (Allenbach et al)

ORTSDavis_A	=	15 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.0306 M

For Mixed Freight Trains (Allenbach et al)

ORTSDavis_A	=	15 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.0766 M

1.1.3 SNCF Formula for Electric Multiple Units

ORTSDavis_A	=	12.75 √(10 M n)	
ORTSDavis_B	=	3.53 M	
ORTSDavis_C	=	0.445 A + 0.521 S + 0.254 P	*for leading vehicle*
	=	0.521 S + 0.254 P	*for following vehicles*

where P *is the number of raised pantographs*

1.1.4 Alstom Formula for TGV-R

ORTSDavis_A	=	7.55 √(10 M n)	
ORTSDavis_B	=	0.283 M	
ORTSDavis_C	=	2.83	*for power cars*
ORTSDavis_C	=	0.445	*for trailer cars*

1.1.5 Empirical Data for Trains

For TGV Duplex DAYSE set M=380, n= 4 + 9, 200.19m x 2.896m x 4.000m (Bosquet):

ORTSDavis_A	=	6338
ORTSDavis_B	=	1.76
ORTSDavis_C	=	5.75

For TGV -POS set M=427 (Jernbanverket):

ORTSDavis_A	=	2760
ORTSDavis_B	=	198
ORTSDavis_C	=	7.41

For TGV -Duplex set M=424 (Alvarez):

ORTSDavis_A	=	2700
ORTSDavis_B	=	115
ORTSDavis_C	=	6.93

For TGV - Réseau set (SYSTRA):

ORTSDavis_A	=	2700
ORTSDavis_B	=	104
ORTSDavis_C	=	6.61

For TGV -Réseau set M=490 (Alvarez):

ORTSDavis_A	=	3800
ORTSDavis_B	=	140
ORTSDavis_C	=	6.61

For TGV -Atlantique set M=416 (Alvarez):

ORTSDavis_A	=	2700
ORTSDavis_B	=	118
ORTSDavis_C	=	7.32

For TGV PSE set (Sjokvist):

ORTSDavis_A	=	3900
ORTSDavis_B	=	148
ORTSDavis_C	=	8.19

For TGV PSE set (Allenbach/Guiheu):

ORTSDavis_A	=	2540
ORTSDavis_B	=	120
ORTSDavis_C	=	7.41

For TGV PSE set M = 418 (Alvarez):

ORTSDavis_A	=	2350
ORTSDavis_B	=	111
ORTSDavis_C	=	6.93

For TGV-001 Experimental set 5-car, M=192, n=6 (Sjokvist):

ORTSDavis_A	=	1040
ORTSDavis_B	=	64.8
ORTSDavis_C	=	3.34

For RTG (5-car) set (Sjokvist):

ORTSDavis_A	=	2070
ORTSDavis_B	=	84.2
ORTSDavis_C	=	7.71

For CC 6500 loco and 10 passenger cars (Sjokvist):

ORTSDavis_A	=	7700
ORTSDavis_B	=	0
ORTSDavis_C	=	12.4

For BB 16500 loco and 7 passenger cars (Sjokvist):

ORTSDavis_A	=	5340
ORTSDavis_B	=	125
ORTSDavis_C	=	11.4

1.2.1 Canadian National Formula (1992)

ORTSDavis_A	=	6.76 M + 80 n	
ORTSDavis_B	=	0.302 M	
ORTSDavis_C	=	0.576 A	*for leading freight locomotive*
	=	0.132 A	*for following freight locomotives*
	=	0.456 A	*for leading diesel rail car*
	=	0.0960 A	*for following diesel rail cars*

For Passenger Locomotives and Carriages (varies with degree of streamlining)

ORTSDavis_C	=	0.456 A	*for leading locomotive or car (conventional)*
	=	0.0840 A	*for following locomotive or car (conventional)*
	=	0.336 A	*for leading locomotive or car*
	=	0.0720 A	*for following locomotive or car*
	=	0.240 A	*for leading locomotive or car*
	=	0.0624 A	*for following locomotive or car*
	=	0.175 A	*for leading high speed locomotive or car*
	=	0.0552 A	*for following high speed locomotive or car*
	=	0.168 A	*for leading locomotive or car (max streamlining)*
	=	0.0480 A	*for following locomotive or car (max streamlining)*

For Freight Wagons

ORTSDavis_C	=	0.118 A	*Box Car*
	=	0.127 A	*Bulkhead Flat (loaded)*
	=	0.288 A	*Bulkhead Flat (empty)*
	=	0.101 A	*Gondola (loaded)*
	=	0.288 A	*Gondola (empty)*
	=	0.170 A	*Covered Hopper*
	=	0.132 A	*Tank Car*
	=	0.120 A	*Standard Flat Car*
	=	0.132 A	*Caboose*
	=	0.295 A	*Multi-level Auto Transporter (Open)*
	=	0.170 A	*Mulit-level Auto Transporter (Closed)*

1.2.2 Canadian National General Values for C (1992)

ORTSDavis_C	=	1.53	*Box Car*
	=	1.65	*Bulkhead Flat (loaded)*
	=	3.75	*Bulkhead Flat (empty)*
	=	0.98	*Gondola (loaded)*
	=	2.81	*Gondola (empty)*
	=	1.95	*Covered Hopper*
	=	1.17	*Tank Car*
	=	0.28	*Standard Flat Car (without trailers)*
	=	1.39	*Standard Flat Car (with trailers)*
	=	1.78	*Caboose*
	=	1.01	*Conventional Passenger Coach*
	=	0.49	*Modern Lightweight Passenger Car*
	=	8.56	*Leading Freight Locomotive*
	=	4.11	*Multi-level Auto Transporter (Open)*
	=	2.69	*Multi-level Auto Transporter (Closed)*

1.2.3 Empirical Data from Canadian Railways

For LRC Diesel Locomotive (Leading) M=113:

ORTSDavis_A = 1154
ORTSDavis_B = 37.3
ORTSDavis_C = 4.05

For LRC Coach M=48:

ORTSDavis_A = 671
ORTSDavis_B = 15.7
ORTSDavis_C = 0.54

1.3.1 USA Original Davis Equations (1926) and Tuthill Modification (1937)

For Diesel and Electric Locomotives and Rail Cars:

ORTSDavis_A = 5.86 M + 129 n
ORTSDavis_B = 0.302 M
ORTSDavis_C = 0.576 A *for leading locomotive or car*
= 0.120 A *for following locomotives or cars*

For Freight Cars:

ORTSDavis_A = 5.86 M + 129 n
ORTSDavis_B = 0.453 M
ORTSDavis_C = 0.120 A

For Passenger Cars:

ORTSDavis_A = 5.86 M + 129 n
ORTSDavis_B = 0.302 M
ORTSDavis_C = 0.0816 A

1.3.2 USA Recommended Values for Use in Davis Formula (Tuthill/Hay c.1940)

For Locomotives and Passenger Cars:

ORTSDavis_A	=	5.86 M + 129 n	
ORTSDavis_B	=	0.302 M	
ORTSDavis_C	=	5.62	*for Locomotives 50 tons*
	=	5.89	*for Locomotives 70 tons*
	=	6.42	*for Locomotives 100 tons and over*
	=	4.54	*for Streamlined Locomotives*
	=	0.91	*for Passenger Cars*

For Rail Cars:

ORTSDavis_A	=	5.86 M + 129 n
ORTSDavis_B	=	0.453 M
ORTSDavis_C	=	*between* 4.28 *and* 5.89

For Freight Cars:

ORTSDavis_A	=	5.86 M + 129 n
ORTSDavis_B	=	0.453 M
ORTSDavis_C	=	*between* 0.95 *and* 1.00

1.3.3 USA Modified Davis Formula (c.1950)

Empirical Formula for Freight Cars:

ORTSDavis_A	=	2.70 M + 89 n
ORTSDavis_B	=	0.101 M
ORTSDavis_C	=	1.70 for conventional equipment
	=	3.57 for piggyback
	=	2.09 for containers

1.3.4 Values for US Railways based on AREMA formula (1999)

RDC diesel multiple unit M=51 L=26:

ORTSDavis_A	=	697	
ORTSDavis_B	=	16.9	
ORTSDavis_C	=	5.50	for leading car
	=	1.16	for trailing car

EMD F40PH diesel locomotive M=118 L=17:

ORTSDavis_A	=	1190	
ORTSDavis_B	=	38.8	
ORTSDavis_C	=	6.54	for leading locomotive
	=	1.25	for trailing locomotive

EMD F59PHI diesel locomotive M=120 L=18:

ORTSDavis_A	=	1200	
ORTSDavis_B	=	39.4	
ORTSDavis_C	=	5.92	for leading locomotive
	=	1.09	for trailing locomotive

EMD GP40H diesel locomotive M=120 L=19:

ORTSDavis_A	=	1200	
ORTSDavis_B	=	39.4	
ORTSDavis_C	=	8.55	for leading locomotive
	=	1.96	for trailing locomotive

GE B32-8WH diesel locomotive M=130 L=20:

ORTSDavis_A	=	1270	
ORTSDavis_B	=	42.7	
ORTSDavis_C	=	8.55	for leading locomotive
	=	1.96	for trailing locomotive

MPX PH36-3C diesel locomotive M=121 L=21:

ORTSDavis_A	=	1210	
ORTSDavis_B	=	39.7	
ORTSDavis_C	=	5.92	for leading locomotive
	=	1.09	for trailing locomotive

1.3.4 Empirical Data for US Railways

Conventional single level coach M=61 L=26:

ORTSDavis_A	=	766
ORTSDavis_B	=	19.9
ORTSDavis_C	=	1.01

Amfleet coach M=55 L=26:

ORTSDavis_A	=	725
ORTSDavis_B	=	18.1
ORTSDavis_C	=	0.49

1.4.1 Indian Railways Broad Gauge Empirical Formulae

Formula for Locomotive:

ORTSDavis_A	=	6.35 M + 130 n
ORTSDavis_B	=	0.329 M
ORTSDavis_C	=	7.24

Resistance for WAP 5 Locomotive based on METI study:

ORTSDavis_A	=	1045
ORTSDavis_B	=	0.23
ORTSDavis_C	=	8.27 (?)

Formula for Passenger Trains:

ORTSDavis_A	=	6.72 M
ORTSDavis_B	=	0.745 M
ORTSDavis_C	=	0.0104 M

Formula for Passenger Trains based on METI study:

ORTSDavis_A	=	14.1 M
ORTSDavis_B	=	0.00893 M
ORTSDavis_C	=	0.0321 M

Formula for LHB Passenger Carriages:

ORTSDavis_A	=	6.85 M
ORTSDavis_B	=	0.776 M
ORTSDavis_C	=	0.0106 M

Formula for Freight Trains:

ORTSDavis_A	=	8.53 M
ORTSDavis_B	=	0.364 M
ORTSDavis_C	=	0.00711 M

Formula for Loaded BOX N wagon:

ORTSDavis_A	=	6.32 M
ORTSDavis_B	=	0.520 M
ORTSDavis_C	=	0.00930 M

Formula for Empty BOX N wagon:

ORTSDavis_A	=	13.1 M
ORTSDavis_B	=	0.370 M
ORTSDavis_C	=	0.0307 M

Formula for Loaded BOX wagon:

ORTSDavis_A	=	8.53 M
ORTSDavis_B	=	0.364 M
ORTSDavis_C	=	0.00711 M

Formula for Empty BOX wagon:

ORTSDavis_A	=	14.9 M
ORTSDavis_B	=	0.379 M
ORTSDavis_C	=	0.0629 M

Formula for BOX E wagon:

ORTSDavis_A	=	13.1 M
ORTSDavis_B	=	0.776 M
ORTSDavis_C	=	0.0307 M

Formula for BOX L wagon:

ORTSDavis_A	=	6.32 M
ORTSDavis_B	=	0.370 M
ORTSDavis_C	=	0.0093 M

Formula for Conraj container wagon:

ORTSDavis_A	=	7.85 M
ORTSDavis_B	=	0.388 M
ORTSDavis_C	=	0.0445 M

Formula for Mulltiple Unit Motor Coach:

ORTSDavis_A	=	7.85 M
ORTSDavis_B	=	1.02 M (?)
ORTSDavis_C	=	4.73 (?)

Formula for Mulltiple Unit Trailer Coach:

ORTSDavis_A	=	13.2 M
ORTSDavis_B	=	0.136 M
ORTSDavis_C	=	0.0210 M

Formula for Main Line EMU Trailer Coach:

ORTSDavis_A	=	6.72 M
ORTSDavis_B	=	0.746 M
ORTSDavis_C	=	0.0104 M

1.4.2 Indian Railways Metre Gauge Empirical Formulae

Formula for Passenger Trains:

ORTSDavis_A	=	15.3 M
ORTSDavis_B	=	0.475 M
ORTSDavis_C	=	0.00381 M

Formula for Freight Trains:

ORTSDavis_A	=	25.5 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.00381 M

1.5.1 Empirical Formulae from Swiss Railways

For Ae 6/6 Locomotive (120 tonnes):

ORTSDavis_A	=	35 M
ORTSDavis_B	=	0.21 M
ORTSDavis_C	=	0.0723 M

For Am 4/6 Locomotive (93 tonnes):

ORTSDavis_A	=	35.6 M
ORTSDavis_B	=	0.336 M
ORTSDavis_C	=	0.0490 M

For Voiture légère Passenger Carriages:

ORTSDavis_A	=	14.7 M
ORTSDavis_B	=	0.154 M
ORTSDavis_C	=	0.0278 M

For Mixed Freight Trains:

ORTSDavis_A	=	15 M
ORTSDavis_B	=	0.105 M
ORTSDavis_C	=	0.0662 M

1.6.1 Empirical Formulae from Japanese National Railways

For Series 0 Shinkansen (Mochizuki):

ORTSDavis_A	=	11.8 M
ORTSDavis_B	=	0.547 M
ORTSDavis_C	=	0.0186 M

For Series 100 Shinkansen (Mochizuki):

ORTSDavis_A	=	12.5 M
ORTSDavis_B	=	0.177 M
ORTSDavis_C	=	0.0176 M

For Series 200 Shinkansen (Mochizuki):

ORTSDavis_A	=	11.5 M
ORTSDavis_B	=	0.544 M
ORTSDavis_C	=	0.0114 M

1.6.1 Empirical Data from Japanese National Railways

For Series 0 Shinkansen 8-car (Sjokvist):

ORTSDavis_A	=	5460
ORTSDavis_B	=	254
ORTSDavis_C	=	8.55

For Series 0 Shinkansen 12-car (Sjokvist):

ORTSDavis_A	=	7710
ORTSDavis_B	=	508
ORTSDavis_C	=	12.7

For N700 Shinkansen 8-car M=356 L=205 (Pawar):

ORTSDavis_A	=	5850
ORTSDavis_B	=	61.0
ORTSDavis_C	=	5.50

1.7.1 Empirical Data from Korean Railways

For KTX TGV (7-car set) 2M+5T, M = 326.3 tonnes, n=20:

ORTSDavis_A	=	1930
ORTSDavis_B	=	92.1
ORTSDavis_C	=	5.07

For Korean Experimental train with new nose (7-car set) 2M+5T, M = 326.3 tonnes, n=20:

ORTSDavis_A	=	1930
ORTSDavis_B	=	92.1
ORTSDavis_C	=	4.31

For TTX Experimental tilting train 6-car set 2M4T, M = 322 (Rho):

ORTSDavis_A	=	7889	(4401) predicted for production model
ORTSDavis_B	=	205	(197) predicted for production model
ORTSDavis_C	=	7.97	(10.2) predicted for production model

1.7.2 Predictive Formulae for Korean Railways

For HEMU 400 (Lee):

ORTSDavis_A	=	13.3 M
ORTSDavis_B	=	0.0481 M
ORTSDavis_C	=	0.272 A + 0.0243 AL

1.8.1 German Railways Empirical Formulae for Freight Trains (Strahl)

For Block Freight Trains:

ORTSDavis_A	=	25.0 M
ORTSDavis_B	=	0.0858 M
ORTSDavis_C	=	0.03 M

For Mixed Freight Trains:

ORTSDavis_A	=	25.6 M
ORTSDavis_B	=	0.172 M
ORTSDavis_C	=	0.06 M

For Empty Wagon Trains:

ORTSDavis_A	=	26.7 M
ORTSDavis_B	=	0.343 M
ORTSDavis_C	=	0.12 M

1.8.2 Empirical Formula for Freight Trains (Nadal)

For four-wheeled wagons mixed loaded and empty:

ORTSDavis_A	=	14.7 M
ORTSDavis_B	=	0.751 M
ORTSDavis_C	=	0.0318 M

1.8.3 Example of German Railways Formula for Passenger Trains (Sauthoff)

For a train of z *Inter-City carriages having total mass* M_Σ *tonnes the* ***sum of the coefficients*** *is:*

ORTSDavis_A	=	$15.4\ (z + 2.7) + 9.81\ M_\Sigma$
ORTSDavis_B	=	$26.5\ (z + 2.7) + 35.3\ b\ M_\Sigma$
ORTSDavis_C	=	$0.884\ (z + 2.7)$

For more information about the Sauthoff equation see section 2.2 below.

1.8.3 German Railways Empirical formulae for Railcars (1933):

For Leading Railcar:

ORTSDavis_A	=	24.5 M	
ORTSDavis_B	=	0	
ORTSDavis_C	=	0.51 A	for bogie railcars with flat ends
	=	0.30 A	for bogie railcars with streamlined ends
	=	0.45 A	for two axle railcars

For Following Railcars:

ORTSDavis_A	=	14.7 M
ORTSDavis_B	=	0
ORTSDavis_C	=	between 0.15 A and 0.18 A for railcars with flat ends
	=	between 0.12 A and 0.15 A for railcars with streamlined ends

1.8.4 University of Hannover's Formula for Air Resistance

If wind direction is ignored, then Hannover's formula approximates to:

ORTSDavis_C	=	0.164 A	for BR 103 electric locomotive
	=	0.082 A	for first Inter City carriage behind locomotive
	=	0.063 A	for intermediate Inter City carriages
	=	0.145 A	for last Inter City carriage in train
	=	0.472 A	for a three car multiple unit train (***sum of all cars***)
	=	0.338 A	for a diesel locomotive with central cab
	=	0.302 A	for BR 51 electric locomotive
	=	0.189 A	for first covered goods wagon behind locomotive
	=	0.063 A	for intermediate covered goods wagons
	=	0.189 A	for last covered goods wagon in train

Note: Area is generally taken as 10 m^2. The values of this factor taken alone seem somewhat low, it is probably better to use the numbers above as values of k_1 in the SNCF equation (1.1).

1.8.5 Sauthoff Formula for Trams, Light Railways and Underground Trains

For Trams:

ORTSDavis_A	=	49 M	
ORTSDavis_B	=	0	
ORTSDavis_C	=	0.04 A	(A = 7.8 m^2)

For Underground Trains:

ORTSDavis_A	=	24.5 M
ORTSDavis_B	=	0
ORTSDavis_C	=	between 0.04 A in open and 0.20 A in tunnels (A = 11 m^2)

For Buses and Trolleybuses:

ORTSDavis_A	=	between 147 M on concrete and 294 M on tarmac	
ORTSDavis_B	=	0	
ORTSDavis_C	=	0.04 A	(A = 7.5 m^2)

1.8.6 Empirical Formulae for Secondary and Branch Line Trains

For Standard Gauge:

ORTSDavis_A	=	20.6 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.0635 M

For Metre Gauge:

ORTSDavis_A = 24.5 M
ORTSDavis_B = 0
ORTSDavis_C = 0.0508 M

For 750mm Gauge:

ORTSDavis_A = 26.5 M
ORTSDavis_B = 0
ORTSDavis_C = 0.0381 M

1.8.9 Empirical Data from DB

For ICE 3 (BR 403) unit (DB-Goethe):

ORTSDavis_A = 4400
ORTSDavis_B = 98.9
ORTSDavis_C = 7.63

For ICE 3 (BR 403) unit M= 409/442 (Railvolution):

ORTSDavis_A = 3580
ORTSDavis_B = 81.2
ORTSDavis_C = 7.15

For ICE 3 (BR 403) unit M=448 L=200 (Pawar):

ORTSDavis_A = 3490
ORTSDavis_B = 128
ORTSDavis_C = 6.40

For ICE 3 (BR 403) unit M=409 ( ):

ORTSDavis_A = 3430
ORTSDavis_B = 125
ORTSDavis_C = 6.32

For ICE T (BR 411) 7-car unit M=399 (Pawar):

ORTSDavis_A = 3510
ORTSDavis_B = 136
ORTSDavis_C = 6.70

For DB Class 120 electric locomotive and 6 passenger cars (Sjokvist):

ORTSDavis_A = 9300
ORTSDavis_B = 100
ORTSDavis_C = 13.5

For DB Class 120 electric locomotive and 6 Eurofima coaches M=324 L=175 (Lukaszewicz):

ORTSDavis_A = 5115
ORTSDavis_B = 0
ORTSDavis_C = 10.1

For DB Class 120 electric locomotive and 10 Eurofima coaches M=484 L=279 (Lukaszewicz):

ORTSDavis_A = 5115
ORTSDavis_B = 0
ORTSDavis_C = 10.1

For BR 423 suburban electric multiple unit M= 105/119 (Railvolution):

ORTSDavis_A = 2740
ORTSDavis_B = 48.2
ORTSDavis_C = 6.48

For BR 611 diesel multiple unit M= 93/115 (Railvolution):

ORTSDavis_A = 1950
ORTSDavis_B = 37.1
ORTSDavis_C = 3.76

1.9.1 Davis Formula for Steam Locomotives

ORTSDavis_A = 6.39 M + 129 n + 98.1 Md
ORTSDavis_B = 0.302 M
ORTSDavis_C = 0.576 A *for leading locomotive or car*
= 0.120 A *for following locomotives or cars*

Where:

Md = Mass on driving axles of locomotive (tonnes)

1.9.2 Sanzin Formula for Steam Locomotives

Sanzin formula for Steam Locomotive and Tender:

ORTSDavis_A = 17.7 Mo + *a* Md
ORTSDavis_B = 0.052 Mo + (*b* / D) Md
ORTSDavis_C = 0.762 A *original Sanzin formula*
= 0.572 A *Chapelon modification*

Where:

Mo = Mass on non-driving axles of locomotive and tender (tonnes)
Md = Mass on driving axles of locomotive (tonnes)
D = Diameter of driving wheels (metre)

Locomotives	*a*	*b*
with 2 coupled axles	54.0	2.82
with 3 coupled axles	68.7	3.53
with 4 coupled axles	78.5	9.88
with 5 coupled axles	86.3	12.7

German empirical formula for tender locomotives with half supply of fuel and water:

ORTSDavis_A = a_1 M
ORTSDavis_B = b_1 M
ORTSDavis_C = 0.102 M

Wheel arrangement	a_1	b_1	Wheel arrangement	a_1	b_1
2-4-0 2-4-2 4-4-2 4-4-4	32.4	0.088	2-8-2 4-8-0 (Goods)	49.0	3.88
2-6-2 2-6-4 4-6-0 4-6-2 4-6-4	41.2	1.09	0-8-0 2-8-0	55.9	4.66
0-6-0 2-6-0	48.1	1.45	2-10-0 2-10-2	59.8	5.93
2-8-2 4-8-2 4-8-0 (Express)	47.1	2.97	0-10-0 2-12-0	65.7	7.34
			0-12-0	77.5	8.82

German empirical formula for tank locomotives with full supply of fuel and water:

ORTSDavis_A = a_2 M
ORTSDavis_B = b_2 M
ORTSDavis_C = 0.127 M

Wheel arrangement	a_2	b_2	Wheel arrangement	a_2	b_2
0-4-2T 2-4-0T 2-4-2T 2-4-4T 4-4-0T 4-4-2T	37.3	0.99	0-8-0T 2-8-0T 2-10-2T	74.6	6.64
0-4-0T 2-6-2T 2-6-4T 4-6-2T 4-6-4T	49.0	1.38	0-10-0T 2-12-2T	81.4	9.50
0-6-0T 0-6-2T 2-6-0T 4-6-0T	60.8	1.98	0-12-0T	94.2	12.4
2-8-2T 4-8-0T 4-8-4T	62.8	4.38			

1.10.1 Empirical Equations from British Railways

For LMS Royal Scot 4-6-0 Locomotive and Tender:

ORTSDavis_A = 38.5 M
ORTSDavis_B = 1.23 M
ORTSDavis_C = 0.0351 M

For LMS Passenger Carriages:

ORTSDavis_A = 11.1 M
ORTSDavis_B = 0.0554 M
ORTSDavis_C = 0.0313 M

1.10.2 Empirical Data from British Railways

For Class 87 electric and 10 Mk II passenger cars (Sjokvist)::

ORTSDavis_A = 6600
ORTSDavis_B = 40.0
ORTSDavis_C = 18.5

For 10 car HST set (2+8) (Sjokvist)::

ORTSDavis_A = 2850
ORTSDavis_B = 64.8
ORTSDavis_C = 10.0

For 10 car HST set M=498 (Hoffrichter):

ORTSDavis_A = 3220
ORTSDavis_B = 113
ORTSDavis_C = 7.80

For APT-P set (2+12) (Sjokvist)::

ORTSDavis_A = 6720
ORTSDavis_B = 98.2
ORTSDavis_C = 10.1

For Class 390 Pendolino 9-car set M=465/501 (RSSB):

ORTSDavis_A = 5310
ORTSDavis_B = 78.1
ORTSDavis_C = 11.8

For Class 390 Pendolino 9-car set M=456 (Hoffricther):

ORTSDavis_A = 5420
ORTSDavis_B = 69.0
ORTSDavis_C = 12.1

For Class 222 Meridian 5-car diesel multiple unit set M=249/268 (RSSB):

ORTSDavis_A = 3200
ORTSDavis_B = 28.5
ORTSDavis_C = 5.76

For Class 357 Elecrostar 4-car electric multiple unit set M=158/180 (RSSB):

ORTSDavis_A = 2160
ORTSDavis_B = 19.4
ORTSDavis_C = 5.39

For Class 450 4-car electric multiple unit set M=172/193 (RSSB):

ORTSDavis_A = 3420
ORTSDavis_B = 34.2
ORTSDavis_C = 5.54

For Eurostar Class 373 20-car 2+18 M=867 L=394 (Rochard):

ORTSDavis_A = 6550
ORTSDavis_B = 82.0
ORTSDavis_C = 23.9

For Inter City Express 8-car electric mulitple unit M=389 (Hoffrichter):

ORTSDavis_A	=	4630
ORTSDavis_B	=	58.9
ORTSDavis_C	=	12.1

For Inter City Express 5-car hybrid mulitple unit M=256 (Hoffrichter):

ORTSDavis_A	=	3044
ORTSDavis_B	=	38.8
ORTSDavis_C	=	12.1

For Inter City Express 8-car hybrid mulitple unit M=405 (Hoffrichter):

ORTSDavis_A	=	4820
ORTSDavis_B	=	61.3
ORTSDavis_C	=	12.1

1.11.1 Empirical Equations from Chinese National Railways

For QJ Locomotive with 6 axle tender:

ORTSDavis_A	=	11.1 M
ORTSDavis_B	=	0.139 M
ORTSDavis_C	=	0.891 M

For QJ Locomotive with 4 axle tender:

ORTSDavis_A	=	7.14 M
ORTSDavis_B	=	0.891 M
ORTSDavis_C	=	0.0909 M

For JS or SY Locomotive:

ORTSDavis_A	=	7.55 M
ORTSDavis_B	=	0.617 M
ORTSDavis_C	=	0.0945 M

For Goods wagon with roller bearings:

ORTSDavis_A	=	9.38 M
ORTSDavis_B	=	0.176 M
ORTSDavis_C	=	0.0169 M

For Goods wagon with friction bearings:

ORTSDavis_A	=	10.9 M
ORTSDavis_B	=	0.0404 M
ORTSDavis_C	=	0.0319 M

For Empty Goods wagon:

ORTSDavis_A	=	22.7 M
ORTSDavis_B	=	0.195 M
ORTSDavis_C	=	0.0911 M

1.11.2 Empirical Data for Chinese High Speed Trains

For CHR1 5M3T M=470, L=200 (Zhao):

ORTSDavis_A	=	5700
ORTSDavis_B	=	37.2
ORTSDavis_C	=	11.88

For CHR2 6M2T M=440, L=200 (Zhao):

ORTSDavis_A	=	3797
ORTSDavis_B	=	32.1
ORTSDavis_C	=	4.90

For CHR5 5M3T M=493, L=200 (Zhao):

ORTSDavis_A	=	5200
ORTSDavis_B	=	37.2
ORTSDavis_C	=	11.88

For CHR380B M=408(523) (Zhao):

ORTSDavis_A	=	3670
ORTSDavis_B	=	36.7
ORTSDavis_C	=	6.65

For CHR380BL 8M8T M=1000, L=400 (Zhao):

ORTSDavis_A	=	7680
ORTSDavis_B	=	193
ORTSDavis_C	=	13.5

For CHR380CL 8M8T M=1000, L=400 (Zhao):

ORTSDavis_A	=	5524
ORTSDavis_B	=	97.2
ORTSDavis_C	=	12.45

1.12.1 Empirical Equations from Swedish Railways

General equation for bogie iron ore wagons:

ORTSDavis_A	=	66 n + 8.83 M
ORTSDavis_B	=	0.2 L
ORTSDavis_C	=	5.4 + 0.114 L

General equation for two axle goods wagons:

ORTSDavis_A	=	65 n + 5.89 M	
ORTSDavis_B	=	0.58 L	
ORTSDavis_C	=	8.2 + 0.133 L	*for mixed freight train*
	=	8.3 + 0.079 L	*for Hbis wagons*
	=	8.3 + 0.149 L	*for Oms wagons*

General equation for X2 high speed train (6-car):

ORTSDavis_A = 550 + 88n
ORTSDavis_B = 0.12 L
ORTSDavis_C = 4.7 + 0.050 L

General equation for passenger train (locomotive plus bogie carriages):

ORTSDavis_A = 1880 + 70n
ORTSDavis_B = 0.19 L
ORTSDavis_C = 8.3 + 0.057 L

Where L *is the length of the vehicle or train (metre).*

1.12.2 Resistance Measurements of Trains from Swedish Railways

Passenger train data:

	Trailing axles	Total mass (tonnes)*	Total length (m)	Track	**A (N)**	**B (N/m/s)**	**C ($N/m/s^2$)**
Loco +1	4	124	40	cwr	**2150**	**8.0**	**6.9**
Loco +5	20	300	145	cwr	**3300**	**28.0**	**10.8**
Loco +9	36	476	251	cwr	**4400**	**48.0**	**14.7**
Loco +9	36	476	251	jointed	**5050**	**113**	**14.9**
Loco +13	52	562	356	cwr	**5500**	**68.0**	**18.6**

* including SJ Re6 electric locomotive mass 74 tons

X2 High speed train data:

	Trailing axles	Total mass (tonnes)*	Total length (m)	**A (N)**	**B (N/m/s)**	**C ($N/m/s^2$)**
M+3T+M	20	300	109	**1600**	**51.6**	**6.22**
M+4T+M	24	318	139	**2000**	**40.0**	**6.90**
M+5T+M	28	398	159	**2300**	**57.8**	**7.74**

For X2 high speed train M=365 ( ):

ORTSDavis_A = 2320
ORTSDavis_B = 74.9
ORTSDavis_C = 7.84

Freight train data (2-axle wagons):

	Trailing axles	Total mass (tonnes)*	Total length (m)	**A (N)**	**B (N/m/s)**	**C ($N/m/s^2$)**
12 mixed	24	579	195	**7000**	**92**	**21.6**
24 mixed	48	1041	355	**11500**	**258**	**37.0**
36 mixed	72	1470	514	**15400**	**279**	**49.2**
18 Hbis loaded	36	797	294	**8000**	**148**	**20.9**
18 Hbis half load	36	581	294	**6750**	**142**	**20.2**
18 Hbis empty	36	395	294	**5600**	**160**	**20.7**
18 Oms	36	798	256	**8050**	**73**	**30.2**

Iron ore wagon data (see 1.11.1 above for derived general equation):

	Trailing axles	Total mass (tonnes)*	Total length (m)	**A (N)**	**B (N/m/s)**	**C ($N/m/s^2$)**
1 Uad empty	4	21.2	9.8	**450**	**-2**	**4.7**
1 Uad half load	4	100.0	9.8	**1100**	**-2**	**4.7**
1 Uad loaded	4	118.8	9.8	**1300**	**-3**	**4.4**
Rm Loco+10 Uad	40	1090.0	100	**12000**	**20**	**16.75**

1.13.1 Empirical Equations from Australian Railways

General equation for bogie iron ore wagons (Szanto):

ORTSDavis_A = 100 n + 4.5 M
ORTSDavis_B = 0
ORTSDavis_C = 0.368 M / 0.551 M loaded/empty

General equation for bogie coal wagons (Szanto):

ORTSDavis_A = 100 n + 4.0 M
ORTSDavis_B = 0
ORTSDavis_C = 1.102 M

1.14.1 Empirical Equations from Serbian Railways

General equation for mixed freight train:

ORTSDavis_A = 4.83 M
ORTSDavis_B = 0.660 M
ORTSDavis_C = 0.0130 M

Measured resistance for JZ 641-300 shunting locomotive:

ORTSDavis_A = 2960
ORTSDavis_B = 3.10
ORTSDavis_C = 5.09

1.15.1 Empirical Data from Spanish Railways

For C-C Locomotive (M=120):

ORTSDavis_A = 1500
ORTSDavis_B = 43.2
ORTSDavis_C = 3.88

For B-B Locomotive (M=80):

ORTSDavis_A = 1000
ORTSDavis_B = 28.8
ORTSDavis_C = 3.88

For 2 Locomotives and 6 passenger cars (M=400):

ORTSDavis_A = 4620
ORTSDavis_B = 140
ORTSDavis_C = 11.7

For TRD Diesel Multiple Unit (M=99):

ORTSDavis_A = 1570
ORTSDavis_B = 9.36
ORTSDavis_C = 4.54

For TRD 598 3-car Diesel Multiple Unit (M=151/173):

ORTSDavis_A = 2040
ORTSDavis_B = 20.5
ORTSDavis_C = 3.89

For Alaris Electric Multiple Unit (M=177):

ORTSDavis_A = 3550
ORTSDavis_B = 115
ORTSDavis_C = 8.60

For S 448 3-car Electric Multiple Unit (M=151/168):

ORTSDavis_A = 1880
ORTSDavis_B = 65.0
ORTSDavis_C = 7.80

For S 594 2-car Diesel Multiple Unit (M=90/108):

ORTSDavis_A = 700
ORTSDavis_B = 38.2
ORTSDavis_C = 5.18

For S 554 ?? (M=90):

ORTSDavis_A = 750
ORTSDavis_B = 25.9
ORTSDavis_C = 2.31

For AVE S 100 10-car / TGV (M=393/421):

ORTSDavis_A = 2540
ORTSDavis_B = 121
ORTSDavis_C = 6.53

For AVE S 102 14-car / Talgo 350 M=322/341 (Alvarez):

ORTSDavis_A = 2880
ORTSDavis_B = 125
ORTSDavis_C = 6.60

For AVE S 102 14-car / Talgo 350 M=322 L=200 (Pawar):

ORTSDavis_A = 2245
ORTSDavis_B = 26.8
ORTSDavis_C = 5.50

For Talgo 350 M=322 (   ):

ORTSDavis_A = 2880
ORTSDavis_B = 125
ORTSDavis_C = 6.46

For AVE S 103 8-car / Velaro E (M=425/485):

ORTSDavis_A = 3560
ORTSDavis_B = 121
ORTSDavis_C = 7.01

For Avant S 104 4-car unit (M=221/242):

ORTSDavis_A = 3270
ORTSDavis_B = 91.1
ORTSDavis_C = 6.48

For Alvia S 120 4-car unit (M=247/275):

ORTSDavis_A = 2250
ORTSDavis_B = 97.6
ORTSDavis_C = 5.83

For Alvia S 130 / Talgo 250 11-car unit M=312/343 (Alvarez):

ORTSDavis_A = 2840
ORTSDavis_B = 86.4
ORTSDavis_C = 7.17

For Talgo 250 11-car unit M=312 ( ):

ORTSDavis_A = 2850
ORTSDavis_B = 86.4
ORTSDavis_C = 6.98

For Alvia S 730 11-car hybrid unit (M=361):

ORTSDavis_A	=	3200
ORTSDavis_B	=	104 electric / 185 diesel
ORTSDavis_C	=	7.13 electric / 6.92 diesel

1.15.2 Empirical Formulae from Spanish Railways

For conventional passenger carriages:

ORTSDavis_A	=	between 15 M and 20 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.288 M

For bogie goods wagons:

ORTSDavis_A	=	between 15 M and 20 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.324 M

For conventional goods wagons:

ORTSDavis_A	=	between 15 M and 20 M
ORTSDavis_B	=	0
ORTSDavis_C	=	0.810 M

1.16.1 Empirical Data from Italian Railways

For AGV-11 set (SYSTRA):

ORTSDavis_A	=	2500
ORTSDavis_B	=	104
ORTSDavis_C	=	5.83

For AGV-11 set M=410 L=200 (Pawar):

ORTSDavis_A	=	6669
ORTSDavis_B	=	39.0
ORTSDavis_C	=	6.10

1.17.1 Empirical Data from Danish Railways

For 1 x IC3 diesel multiple unit M=88 L=59 (Lindgreen):

ORTSDavis_A	=	1620
ORTSDavis_B	=	47.2
ORTSDavis_C	=	4.58

For 2 x IC3 diesel multiple units M=176 L=118 (Lindgreen):

ORTSDavis_A	=	3210
ORTSDavis_B	=	78.5
ORTSDavis_C	=	7.23

For 3 x IC3 diesel multiple units M=264 L=176 (Lindgreen):

ORTSDavis_A = 4480
ORTSDavis_B = 110
ORTSDavis_C = 9.89

For 5 x IC3 diesel multiple units M=440 L=294 (Lindgreen):

ORTSDavis_A = 7960
ORTSDavis_B = 172
ORTSDavis_C = 15.2

For 1 x IC regional electric multiple unit M=121 L=77 (Lindgreen):

ORTSDavis_A = 2100
ORTSDavis_B = 56.6
ORTSDavis_C = 5.41

For 2 x IC regional electric multiple unit M=241 L=153 (Lindgreen):

ORTSDavis_A = 4160
ORTSDavis_B = 97.2
ORTSDavis_C = 8.88

For 3 x IC regional electric multiple unit M=241 L=153 (Lindgreen):

ORTSDavis_A = 6230
ORTSDavis_B = 138
ORTSDavis_C = 12.4

For MR-Local diesel multiple unit M=63 L=45 (Lindgreen):

ORTSDavis_A = 2500
ORTSDavis_B = 19.9
ORTSDavis_C = 0.53

2. Further Information Regarding German Equations

German Railways use the Sauthoff formula to calculate the resistance of passenger trains and the Strahl formula to calculate the resistance of freight trains. In the case of locomotive hauled trains the resistance of the locomotive is calculated separately from that of the train using either the Sanzin formula for a steam locomotive or the ??? for a diesel or electric locomotive.

Calculations generally included the effects of wind, shown as ΔV, in the formulae. The equivalent of a 15 km/h head wind is taken as standard in these calculations.

Whilst the Strahl formula can be used directly to calculate values for Open Rails, the Sauthoff formula can not be used in this way. If you wish to apply the Sauthof formula for a particular train then you would calculate the total resistance for the train and then divide up the result between the vehicles that make up the train. This reflects observations made also in the United Kingdom and in Australia that longer trains have proportionately less air resistance than shorter trains.

Since both the Strahl and Sauthof formulas are not normally presented in the same format as the Davis equation, the equations have to be rearranged to determine the coeffients A, B and C.

2.1 Strahl Formula

Today the Strahl formula is used in the form:

$$r = \frac{1}{10}\left[25 + k\left(\frac{V + \Delta V}{10}\right)^2\right]$$

Where r is resistance (kg/tonne), k is a constant depending on the type of train, and V is the train speed (km/h). Taking ΔV as 15 km/h this becomes:

$$r = \frac{1}{10}\left[25 + k\left(\frac{V + 15}{10}\right)^2\right]$$

Expanding the brackets gives:

$$r = 2.5 + 0.225k + 0.03kV + 0.001kV^2$$

Converting into Newtons, metres and seconds, for a train of mass M tonnes the resistance:

$$R = (24.5 + 2.21k)M + 1.059kMV + 0.127kMV^2$$

From which:

ORTSDavis_A = (24.5 + 2.21*k*) M
ORTSDavis_B = 1.059*k* M
ORTSDavis_C = 0.127*k* M

Where *k* = 0.25 for block freight trains
k = 0.33 for express freight trains
k = 0.5 for mixed freight trains
k = 1.0 for empty wagon trains

The earlier form of the Strahl formula did not include and addition for wind. Giving the resistance in *Newtons per tonne* as:

$$R/M = 25 + k\left(\frac{V}{10}\right)^2$$

This gives:

ORTSDavis_A = 25 M
ORTSDavis_B = 0
ORTSDavis_C = 0.1*k* M

2.2 Sauthoff Formula

The general form of the Sauthoff Formula as used for main line railways is:

$$r_\Sigma = a\, M_\Sigma + b\, M_\Sigma V + 0.0048\,(z + 2.7)\, f\,(V + \Delta V)^2$$

Where M_Σ is the total mass of the train in tonnes, and z is the number of vehicles in the train. The term $(z + 2.7)$ increases the air resistance of the whole train to represent the drag of the rear vehicle. Taking ΔV as 15 km/h the equation becomes:

$$r_\Sigma = a\, M_\Sigma + b\, M_\Sigma V + 0.0048\,(z + 2.7)\, f\,(V + 15)^2$$

Converting into Newtons, metres and seconds:

$$R_\Sigma = 9.81\, a\, M_\Sigma + 35.3\, b\, M_\Sigma V + 0.610\,(z + 2.7)\, f\,(V + 15)^2$$

Expanding this gives:

$$R_\Sigma = 137\,(z + 2.7)f + 9.81\, a\, M_\Sigma + (18.3\,(z + 2.7)f + 35.3\, b\, M_\Sigma)\, V + 0.610\,(z + 2.7)\, f\, V^2$$

Making ***the sum of*** the coefficients of the Davis equation ***for the train***:

ORTSDavis_A	=	$10.6\,(z + 2.7)\, f + 9.81\, a\, M_\Sigma$
ORTSDavis_B	=	$18.3\,(z + 2.7)\, f + 35.3\, b\, M_\Sigma$
ORTSDavis_C	=	$0.610\,(z + 2.7)\, f$

The values of the constants a, b and f are given by:

$a = 1.9$ for friction bearings
$a = 1.0$ for roller bearings

$b = 0.0025$ for bogie carriages
$b = 0.004$ for six-wheeled carriages
$b = 0.007$ for four-wheeled carriages

f is the equivalent cross sectional area of the carriage, with f = 1.45 equivalent to an area of $10m^2$.

$f = 1.45$ for modern main line carriages
$f = 1.55$ for older German bogie carriages (pre-1930)
$f = 1.15$ for 4-wheeled and 6-wheeled carriages

A more simple version of the Sauthoff formula having the form $R = a\,M + c\,A\,V^2$ is used for trams, light railways and underground systems.

3. Armstrong-Swift Equations

Armstrong and Swift developed a set of equations for determining the Davis coefficients for British Electric Multiple Unit trains. The equations are somewhat limited in their use as they can only be applied to electric trains with a Motor Car : Trailer Car ratio of 1 : 3 or less. The equations do however give good results for suburban multiple units and have been shown to work for high speed trains with a high proportion of motorised vehicles such as Shinkansen trains and the ICE 3.

These equation gives ***the sum of*** the coefficients of the Davis equation ***for the train*** as:

ORTSDavis_A = $6.3\ M_{TC} + 7.9\ M_{PC}$
ORTSDavis_B = $0.18\ (M_{TC} + M_{PC}) + 1.0\ n_{TC} + 0.005\ n_{PC}\ P$
ORTSDavis_C = $0.6125\ C_x\ A + 0.00197\ S_\Sigma + 0.0021\ sg\ (n_{TC} + n_{PC} - 1) + 0.2061\ C_b n_B + 0.256\ n_P$

Where:

M_{TC} = total mass of trailer cars (tonnes)
M_{PC} = total mass of power cars (tonnes)
n_{TC} = number of trailer cars
n_{PC} = number of power cars
P = total power output (kW)
C_x = head/tail drag coefficient
S_Σ = surface area of the train m^2 (perimeter x Length)
sg = surface area of the inter-vechicle gap (perimeter x distance between cars)
C_b = bogie drag coefficient
n_B = number of bogies
n_P = number of pantographs

Whilst the equation gives a detailed breakdown of the components of the C coefficient it has been found more recently (Baker 2014) that this gives an overestimate for the air resistance of modern high speed trains.

4. RSSB Method

The Rail Safety and Standards Board of the United Kingdom has put forward a method of calculating the parameters in the Davis Equation which can be summarised as follows:

ORTSDavis_A = *k* M   with k typically having a value of 12

ORTSDavis_B = 0.064 M + B_2

B_2 is the mass of air (in kg) used for traction motor cooling and passenger ventilation. As this is difficult to quantify Esters and Marinov have suggested that this factor might be omitted, which gives simply:

ORTSDavis_B = 0.064 M

The coefficient of the quadratic factor is made up of several parts representing different aerodynamic resistance factors, which can be summarised as:

ORTSDavis_C = $\rho/2\ C_D\ A$

Where ρ is the density of air at operating temperature, taken as 1.247 kg/m^3 at 10° C in UK and C_D is the drag coefficient of a particular train given by:

$C_D = C_{DHT} + C_{DL} + C_{DB} + C_{DI} + C_{DE}$

C_{DHT} = head and tail drag coefficient, between 0.6 for freight and 0.19 for high speed train

C_{DL} = length drag coefficient = L_F L   L being train length and L_F between 0.004 and 0.005

C_{DB} = bogie drag factor = 2 Nv B_F Nv = number of vehicles and B_F between 0.02 and 0.03

C_{DI} = 0.025 (Nv – 1)

C_{DE} = 0.06 n_P n_P = number of pantographs

5. Conversion Factors

1 kg force	=	9.81 Newton
1 kg force/kilometre/hour	=	35.3 Newton/metre/second
1 kg force/(kilometre/hour)^2	=	127 Newton/(metre/second)^2
1 kilometre/hour	=	0.278 metre/second
1 ton UK	=	1.016 tonne
1 ton US	=	0.907 tonne
1 foot	=	0.305 metre
1 square foot	=	0.0929 metre^2
1 mile per hour	=	0.447 metre/second
1 metre/second	=	2.237 miles per hour
1 lb force	=	4.45 Newton

6. Sources

Allenbach, Jean-Marc, Chapas, Pierre, Comte, Michel and Kaller Roger. "*Traction Électrique, Volume 1*". Presses Polytechniques Et Universitaires Romandes, Lausanne, Switzerland 2008. pp 42-43.

Álvarez, García. *"Dinámica De Los Trenes En Alta Velocidad."* Dinámica De Los Trenes En Alta Velocidad, Fundación De Los Ferrocarriles Españoles, 2006, myslide.org/traccion-y-dinamica-de-trenes. [Accessed: 20 Aug 17].

Álvarez, García. *"Dinámica De Los Trenes En Alta Velocidad."* Dinámica De Los Trenes En Alta Velocidad, Fundación De Los Ferrocarriles Españoles, 2015, www.slideshare.net/IgnacioGonzlezFranco/dinmica-de-los-trenes-en-alta-velocidad. [Accessed: 20 Aug 17].

AREMA *"Section 2.1 Resistance to Movement."* 1999 Manual for Railway Engineering, American Railway Engineering and Maintenance-of-Way Association, 1999.

Boschetti, Giorgio & Mariscotti, Andrea. *"The parameters of motion mechanical equations as a source of uncertainty for traction systems simulation."* 20th IMEKO World Congress 2012. 2. 897-902.

Bosquet, Romain & Vandanjon, Pierre & Coiret, Alex & Lorino, Tristan. (2013). *Model of high-speed train energy consumption*.

DB *"Das System Bahn: Der ICE"*, Goethe-Gymnasiums Regensberg, 2013. www1.deutschebahn.com/file/dbst-de/11420656/FT0kWxrU4O58qibBq4zGkMid8Ac/13795544/data/schulbroschuere_regensburg_system_bahn_ice.pdf. [Accessed: 18 Aug 17].

Esters, T, and M Marinov. "An Analysis of the Methods Used to Calculate the Emissions of Rolling Stock in the UK." *Transportation Research Part D: Environment and Transport*, vol. 33, 2014, pp. 1–16. doi:http://dx.doi.org/10.1016/j.trd.2014.08.012.

Hay, William W. "*Railroad Engineering*." Vol. 1, John Wiley & Sons, 1982.

Indian Railways RDSO *"Technical Circular No 27"* (1998), rdso.indianrailways.gov.in/works/uploads/File/TC_27(1).pdf, Indian Railways, n.d. [Accessed: 17 Aug 17].

Ishizu, K, and J Miyakaw. "Aerodynamic Design of JR300X Frontal Shape by Computational Fluid Dynamics." *Transactions on the Built Environment*, vol. 6, 1994, pp. 337–344., www.witpress.com/Secure/elibrary/papers/CR94/CR94041FU.pdf. [Accessed: 11 Aug 17].

Johansen, F C. "The Air Resistance of Passenger Trains." *Proceedings of the Institution of Mechanical Engineers*, vol 134, June 1936. pp. 91-208.

Kim, S-W, Kwon, H-B, Kim, Y-G and Park, T-W. "Calculation of Resistance to Motion of a High-Speed Train Using Acceleration Measurements in Irregular Coasting Conditions." *Proceedings* *of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Volume: 220 Part: F4, December 2016, pp. 449-459

Lee, Taehyung, et al. *“A Study of the Train Performance Simulation for Korean next Generation High Speed Train.”* May 2011, www.railway-research.org/IMG/pdf/poster_taehyung_lee.pdf.

Lamalle, Ulysse. *“Cours D'exploitation Des Chemins De Fer - La Voie”* published in print Dunod 1951. www.tassignon.be/trains/cecf/tomeIV/C_E_C_F_IV.htm#p021. [Accessed: 10 Aug 17].

Lukaszewicz, Piotr. *“Energy Consumption and Running Time for Trains : modelling of running resistance and driver behaviour based on full scale testing”* (PhD dissertation). Stockholm 2001. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-3185 [Accessed 17 Aug 17].

Lukaszewicz, Piotr. “Running Resistance and Energy Consumption of Ore Trains in Sweden.” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 223, no. 2, 1 Dec. 2008, pp. 189–197.

Meineke, F. *“Die Dampflokomotive: Lehre Und Gestaltung.”* Die Dampflokomotive, Springer-Verlag Berlin Heidelberg, 8 Mar. 2013, www.springer.com/gp/book/9783642862304.

Mochizuki, Asahi. “Conventional Line Speed Increases and Development of Shinkansen.” *Japan Railway & Transport Review*, no. 57, Mar. 2011, pp. 42–49

Pritchard, J., *"Investigating the Operational Energy Consumption of a Train - Understanding the Factors Which Affect it, and the Potential of Rail to be a Sustainable Mode of Transport."* WCTR 2013. http://www.wctrs.leeds.ac.uk/wp/wp-content/uploads/abstracts/rio/general/3087.pdf [Accessed 20 Aug 17]

Profillidis, V. A. *“Railway management and engineering”*, 3rd ed., Aldershot, UK, Ashgate c2006 “Chapter 18 Train Dynamics”

Radosavljevic, A. “Measurement of Train Traction Characteristics.” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 220, no. 3, May 2006, pp. 283–291.

Railvolution, “Next Generation Train – The Revolution”, *Railvolution*, no4, 2012 www.railvolution.net/railvolution/archive/2012/4

“Resistance.” Advanced Steam Traction, www.advanced-steam.org/5at/technical-terms/steam-loco-definitions/resistance/. n.p., n.d., [Accessed 17 Aug 17].

Rho, H.L., Han, S.H., Kim, G.S., *"Development of the Korean Tilting Train and Its Simulated Run-time Comparison with Non-tilting Train on the Central Line."* Association for European Transport, 2011, abstracts.aetransport.org/paper/download/id/3669 [Accessed 20 Aug 17].

RSSB. *“Quantification of benefit of train mass reduction.”* T712_anxE.pdf. RSSB (2010).

Sjokvist, Erik H. *"Worldwide development of propulsion systems for high-speed trains."* Transportation Research Record 1177 (1988).

Szanto, Frank. *“Rolling resistance revisited”* [online]. In: CORE 2016: Maintaining the Momentum. Melbourne: Railway Technical Society of Australasia, 2016: 628-633. <http://search.informit.com.au/documentSummary;dn=437053418057936;res=IELENG> ISBN: 9781922107800. [Accessed 10 Aug 17].

The Railway Executive, *“Report on Trials of L.M.R. 2-6-0 Class 2 Loco. No. 46413 for the Locomotive Testing Committee. W8”.* The Railway Executive, Swindon 1950. Archive Document at the National Railway Museum York, UK (692 TEST LMS 12 London Midland & Scottish Locomotive Test Reports 2 2-6-0 1947-1950)

UIC, www.join-and-share.de. *“Streamlining of Head and Tail.”* Energy Efficiency Technologies, www.railway-energy.org/static/Streamlining_of_head_and_tail_14.php. [Accessed: 11 Aug 17].

Wikipedia, “SNCF TGV Duplex.” Wikipedia, Wikimedia Foundation, 6 Aug. 2017, en.wikipedia.org/wiki/SNCF_TGV_Duplex. [Accessed: 11 Aug 17].

Zhao, Hai-Bo. “Relationship between Energy Consumption and Speed of the EMU.” *Proceedings of the 2016 4th International Conference on Electrical & Electronics Engineering and Computer Science (ICEEECS 2016),* 2016, doi:10.2991/iceeecs-16.2016.116.